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Alternative weed management practices: Effects on weed control, grapevine performance, and soil quality in an established midwestern vineyard

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ABSTRACT

Sustainable grape production entails the implementation of management practices that control weeds, maintain grapevine performance, and conserve soil quality. Conventional weed management practices include herbicide application and/or cultivation. These practices compromise soil quality by limiting additions of organic matter and exposing the soil surface, thereby leaving it prone to degradative processes. With the expansion of continental climate viticulture in areas with rain-fed agriculture, such as in the Midwest, there is a need for sustainable weed management practices that optimize production while conserving soil quality. The primary objective of this investigation was to evaluate weed management practices in an established midwestern vineyard. Sub-objectives of the investigation addressed within individual experiments include: 1) comparing conventional and alternative weed management practices on weed control, grapevine performance, and soil quality, and 2) evaluating the influence of irrigation on grapevine growth and development, grown with and without a living mulch, on mitigation of water competition. An additional objective of this investigation was to survey Iowa fruit growers' attitudes and awareness of weed management practices that conserve soil resources.

In the first experiment, two conventional and two alternative weed management strategies were compared in an established Iowan vineyard with 'Maréchal Foch' grapevines (*Vitis rupestris* Scheele ×*vinifera* L.). Treatments were replicated four times in a randomized complete block design and included: 1) cultivation, 2) herbicide application, 3) straw mulch, and 4) a living mulch of creeping red fescue (*Festuca rubra* L. 'Pennlawn'). Straw and living mulches controlled weed populations and grapevine yield did not differ among the treatments. Dormant cane pruning weights and fruit quality were lowest in

cultivated and straw mulch plots, respectively. Mulched plots had greater water-filled pore space and water content, as well as faster infiltration rates. No differences in chemical soil quality attributes were observed. Although earthworm populations were greater in straw mulch plots, no differences in soil enzymatic activity were found. Results from the experiment demonstrate straw and living mulches reduce weed populations, maintain grapevine productivity, and improve several indicators of soil quality.

The effects of living mulches, with and without irrigation, on grapevine growth and development were measured in the second experiment. Data were collected from an established vineyard in Iowa with ‘Reliance’ and ‘Swenson Red’ grapevines (*Vitus labrusca* L.) planted in a randomized complete block design. Treatments were replicated eight times and included: 1) herbicide application without irrigation, 2) herbicide application with irrigation, 3) living mulch without irrigation, and 4) living mulch with irrigation. The living mulch treatment was a mixture of shade-tolerant creeping red and Chewings fescue [*Festuca rubra* L. ‘Foxy’ and *F. rubra* var. *fallax* (Thuill.) Hack. ‘Ambrose,’ respectively]. Supplemental irrigation was provided via drip irrigation and scheduling regimes were based on fescue evapotranspiration. Living mulches and irrigation had no consistent effect on grapevine growth and development, suggesting little-to-no competition existed between the grapevines and living mulches during the period in which the study was conducted. When compared to both herbicide-treated plots, living mulches reduced weed populations and promoted several indicators of soil quality.

Results from both experiments demonstrate the alternative practices of straw and living mulches control weeds, maintain grapevine performance, and may be viable alternatives to vineyard weed management that promotes soil quality within the Midwest.

While results from the experiments suggest alternative weed management practices may contribute to the sustainability of a weed management system, grower receptiveness to alternative practices is important when planning future extension-education programs and advancing soil-quality awareness. Within a survey of twenty-two Iowa fruit growers, all survey participants were aware of soil quality and considered the quality of their soils when making land management decisions. Most were aware of alternative weed management practices, yet were uncertain about the outcome of implementing alternative practices within their own production systems. To further advance the awareness and adoption of soil-quality concepts and alternative weed management practices, respectively, future extension programs should focus on educating growers how weed management decisions can impact both crop productivity and soil quality.

CHAPTER 1. GENERAL INTRODUCTION

Thesis Organization

The following thesis consists of five chapters. Chapter one is a general introduction to the study and includes a review of relevant literature pertinent to the investigation. Chapters two and three were prepared as manuscripts to be submitted to the *American Journal of Enology and Viticulture*, while the fourth chapter was prepared in a format to be submitted to *HortTechnology*. General conclusions for the overall study are provided in chapter five.

Introduction

With the recent expansion of the Iowa grape and wine industry, there is a need to develop sustainable weed and soil management practices. Midwest states, like Iowa, are known for having strong agricultural economies. While Iowa has long been the United States' leading producer of corn and soybeans, the state also has a history of grape and wine production (USDA 2008). In 1919, Iowa was the sixth largest grape producer in the United States (White and Dharmadhikari 2008). Due to the sequence of prohibition, the introduction of 2,4-D herbicides that damage grapevines, increased row crop production, and the Armistice Day Freeze of 1940, grape production in Iowa fell. Yet, production began to increase in the late 1990s. From 1999 to 2009, the number of commercial vineyards in Iowa expanded from 15 to approximately 400, some of which serve 74 state-licensed wineries (Midwest Grape and Wine Industry Institute 2008; White 2009). As of 2006, about 260 hectares (650 acres) of Iowa land was dedicated to grape production (Midwest Grape and Wine Industry Institute 2008). Production in other midwestern states, which all share continental climates that are relatively new to grape production, has also increased (Gartner and Tuck 2008; Read 2004; Shoemaker and Campbell 2007). With this rapidly reemerging industry, sustainable land management practices that are environmentally sound, economically viable, and socially responsible are needed (Ingles 1992; Pirog 2000). Sustainable vineyard management includes implementation of weed management practices that effectively control weeds, promote grapevine productivity and fruit quality, and maintain soil quality.

The primary objective of this investigation was to evaluate the influence of alternative weed management practices on weed control, grapevine performance, and soil quality in an established Iowan vineyard. Specific sub-objectives addressed within individual experiments include: 1) comparing conventional and alternative weed management practices on weed control, grapevine performance, and soil quality, and 2) evaluating the influence of irrigation on grapevine growth and development, grown with and without a living mulch, on mitigation of water competition. An additional objective of this investigation was to survey Iowa fruit growers' attitudes and awareness of weed management practices that conserve soil resources. With survey information, changes in attitude and awareness can be recorded, analyzed, and/or utilized in developing future extension-education programs.

Literature Review

Importance of sustainable land management

Conventional agricultural practices can degrade soils, thereby affecting the productivity and resilience of the land and surrounding ecosystems. Certain practices common in conventional viticulture, such as maintaining bare soil through continual herbicide use and/or cultivation, exacerbate soil quality losses and the overall sustainability of a vineyard production system (Ingles 1992). Without protective groundcovers, bare soil is susceptible to physical forces that favor erosion. For example, raindrop impact can dislodge soil particles, thereby permitting lateral movement of dislodged particles to off-site locations. Such movement can have both negative on- and off-site consequences, including declines in crop productivity and pollution of surface waters (Lal et al. 2004).

Estimates made by Pimentel et al. (1995) found approximately 1/3 of Earth's arable land has been impacted due to water and wind erosion. On-site damages incurred by erosion include reduced organic matter content, fertility, infiltration, water holding capacity, and biological activity. To counteract losses in soil fertility (most notably from nitrogen, phosphorus, potassium, and calcium adhering to moving soil particles), growers often increase rates of fertilizer applications, which increase growers' financial burdens and creates additional environmental concerns (Tegtmeier and Duffy 2002). Siltation, sediment deposition, destruction of navigable waterways, eutrophication, and ecological damages through habitat destruction are several of the off-site consequences of erosion. Many of these risks can be averted by the implementation of erosion-preventative and soil-conserving practices that provide groundcover to slow the movement of soil particles (Chiras et al. 2002; Pimentel et al. 1995).

Excessive use and/or mismanagement of agrichemicals have also been noted to have detrimental environmental impacts. Although pesticide usage has been attributed to agricultural production increases within the past century, some of the indirect effects of pesticides include accidental exposure to applicators and field workers, residuals and runoff contributing to public health risks and environmental pollution, decreases in non-target and/or beneficial organism populations, and evolved resistance in target organism populations (Pimentel et al. 1992). Pimentel et al. (1997) highlighted that losses in biodiversity can impair agricultural production by reducing populations of organisms that perform biological services. Examples of beneficial biological services include soil formation through soil biological activity, plant pollination, nutrient cycling, nitrogen fixation, and biological pest control. Additionally, the indirect effects of herbicide damage and drift are of vital concern for grapes and other herbicide-sensitive crops (Leonard and Lider 1961).

Agriculture and related activities use large amounts of energy via production of agrichemical inputs, as well as through usage of vehicles and mechanized equipment before, during, and after crop production. Much of this energy is derived from non-renewable energy sources that contribute to the emission of greenhouse gases and other pollutants. With rising energy demands and costs, energy-consumption awareness is becoming a frequent part of public discourse and land management decisions. Growers and the public alike are becoming increasingly interested in minimizing energy usage, as well as substituting energy-intensive inputs for more sustainable resources. Sustainable production methods can also internalize some of the costs and consequences of conventional agricultural production (Ingles 1992; Tegtmeier et al. 2004).

Long-term consequences of current weed and land management practices jeopardize the ultimate sustainability of vineyard operations, as well as the future productivity of soils. Given the risks of land mismanagement, the investigation, dissemination, and adoption of sustainable vineyard land management practices that conserve and/or promote soil quality are essential in ensuring long-term productivity.

Soil quality

As defined by the Soil Science Society of America, soil quality is “the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and to support human health and habitation” (Karlen et al. 1997). To evaluate soil quality, emphasis is often placed on assessments at the functional level, which includes consideration of chemical, physical, and biological soil properties and processes (Doran and Jones 1996; Karlen et al. 1997; USDA 1999). Examples of measurable chemical soil properties include pH, cation exchange capacity (CEC), and nutrient content and availability. Measureable physical properties include aggregate stability, bulk density (compaction), water infiltration and retention, and pore size space and distribution (Karlen et al. 1997). Examples of measurable biological properties include plant growth and productivity, earthworm counts, mycorrhizal associations, soil enzyme activity, and microbial biomass and respiration (Karlen at al. 1997). While the implications of declines in chemical and physical soil properties are largely recognized, the importance of biological properties is often unmentioned. Soil biota and their activities are critical components in the health and productive capacity of soils. Known benefits of soil biota include nutrient cycling, organic matter decomposition, nitrogen fixation, production of soil humic substances, particle aggregation, degradation of xenobiotics, and soil mixing and aeration (Blair et al. 1996; Dick et al. 1996; Sylvia et al. 2005).

Developers of the soil quality concept advocate that evaluations take a holistic approach whereby both sensitive and subtle changes in the soil environment are monitored and correlated to land management practices through the evaluation of multiple soil quality indicators (Bezdicek et al. 1996). Measurement of soil properties recognized as quality indicators is followed by comparison to known and/or desired values for a given indicator (Karlen et al. 1997). With this approach, regular monitoring can assist growers with land management decisions by enabling them to identify and potentially mitigate management practices that degrade soils. Practices that promote soil quality for a given location can also be recognized and encouraged for growers to adopt, thereby favoring sustainable land management.

Within perennial fruit production systems, conventional weed management practices based on herbicides and/or cultivation have been noted to diminish soil quality and resulting fruit productivity (Merwin and Pritts 1993). Research by Glover et al. (2000) found that consistent use of herbicides in apple orchard production systems negatively affected soil properties such as aggregate stability, microbial biomass, and earthworm counts, while increasing bulk density. Many of these properties are indicators of soil quality and are essential in maintaining soil tilth and fertility, as well as the long-term productivity of an agricultural enterprise. For example, increases in bulk density have been associated with decreases in shoot growth, leaf area and biomass, and number of inflorescences in container-grown grapevines (Ferree and Streeter 2004; van Huyssteen 1988). In an established Iowan vineyard, Dilley (2007) observed continual cultivation decreased grapevine yield, while bulk density concomitantly increased.

The predominate mechanism responsible for observed losses in soil quality with conventional weed management is due to reductions of soil organic matter input. Weed control practices dependent on herbicide application and/or cultivation reduce vegetative groundcover and, consequently, soil organic matter input. As a result, soil erosion and loss of soil structure are exacerbated, while nutrient and water holding capacity, infiltration, and soil biological activity are reduced (Dilley 2007; Glover et al. 2000; Merwin et al. 1994; Stamatiadis et al. 1996). Smith et al. (2008) re-confirmed these findings, but also observed management practices that minimize vegetative groundcover in a vineyard production system have higher amounts of runoff and suspended soil particles in collected runoff, implicating accelerated water erosion relative to treatments that maintain a vegetative groundcover.

Defining what constitutes optimal soil quality in vineyard production systems is vaguely understood and in need of elucidation (van Es 2008). Many of the famous wine-growing regions of the world are from geographic areas with a recognized *terroir*. While debate surrounds the merit of the *terroir* concept, it is usually defined as the characterization of a site based on temporary and permanent factors (White 2003). Temporary factors include cultivar, cultural production practices, and wine-making techniques, while permanent factors include climate, topography, and soils. High-quality viticultural soils are often considered to be of marginal or poor quality relative to other horticultural and agronomic crops. For example, soils with high nitrogen availability are undesirable because of subsequent stimulation of grapevine vegetative growth, which complicates canopy management, compromises fruit quality, and decreases yields by reducing bud fruitfulness (Wolf 2008). Low midseason soil water retention has also been found to favor better wine sensory attributes (van Es 2008). Nevertheless, reductions in tillage and maintenance of groundcovers with natural and/or synthetic mulches are reputed to promote vineyard soil quality and long-term sustainability (Ingles 1992). Despite these findings, research is needed in defining soil quality for vineyard production systems, particularly for locations with emerging, or reemerging, grape-growing industries.

Few studies on vineyard weed management and soil quality have been conducted within the Midwest. With the Midwest's rapidly reemerging grape and wine industry, it is of paramount importance to raise grape growers' awareness of soil quality and sustainable land management. Furthermore, the development and growth of a sustainable grape and wine industry in the Midwest depends largely upon the implementation of effective weed control practices that maintain both grapevine performance and soil quality.

Vineyard weed management

Weeds compromise crop productivity through competition for plant resources including water, soil nutrients, and light. In some instances, weeds harbor and vector plant pests and pathogens (Wisler and Norris 2005). While largely unrecognized, weeds are often the most limiting factor of crop production (Elmore 1996). Left unabated, weeds threaten grapevine performance and vineyard productivity—particularly in organic vineyards where herbicide use is limited (Delate and Friedrich 2004; Sanguankeo et al. 2009). Conventional techniques for managing weed populations in the Midwest entail pre- and post-emergent herbicide applications and/or mechanical cultivation (otherwise known as "tillage") underneath the vineyard trellis, while permanent vegetative groundcovers are maintained between rows. The short-term effectiveness of herbicides and cultivation has enabled midwestern growers to successfully cultivate grapes. However, concern regarding the long-term consequences of conventional weed management has created recent interest in alternative practices that provide effective weed control, while minimizing the negative environmental impacts associated with conventional weed management.

Alternative weed management practices

Historically, groundcovers were one of multiple methods that growers utilized to address problems of erosion and declining soil productivity (Hartwig and Ammon 2002; Paine and Harrison, 1993). Research has indicated that non-living mulches, including straw and geotextiles, are effective at controlling weeds while maintaining grapevine productivity and soil quality (Hostetler et al. 2007; Pool et al. 1990; Sandler et al. 2009). Yet, non-living mulches are expensive and impractical in many production systems. Investigators working with geotextiles have also noted its susceptibility to tearing and breaking, which translates into additional labor costs in re-application of the mulch to maintain its efficacy (Hostetler et al. 2007; Sandler et al. 2009).

Cover crops are living groundcovers planted prior to or after vineyard establishment and may be maintained on an annual, semi-permanent, or permanent basis. In some cases, cover crops may be intercropped and/or plowed into the soil as a source of green manure. Within vineyards, cover crops are utilized for a variety of reasons. Depending on a grower's goals, cover crops may be implemented to control weeds, reduce soil erosion, improve soil structure, modify fertility, regulate grapevine vigor, and/or provide a habitat for beneficial organisms (Derr 2008). Permanent living cover crops, commonly referred to as "living mulches" or "sward," are maintained as companion crops and may be planted between or within vineyard rows. Reputed benefits of living mulches include reduction of weed populations, soil erosion, and agrichemical runoff (pollution), while soil structure, fertility, predatory insect pest populations, and overall crop productivity are improved (Hartwig and Ammon 2002; Paine and Harrison 1993).

Despite the noted ability of living mulches to improve soil quality attributes, information regarding their competitive effects on grapevine growth, development, and fruit quality is conflicting. Competition and consequent declines of woody perennial plant growth is known to occur when planted with warm-season and cool-season turf grass species (Griffin et al. 2007). When comparing 175 potential cover crop species (including living mulches) within Washington orchards and vineyards, Olmstead et al. (2001) found grass mixes [specifically crested wheatgrass (*Agropyron cristatum* L.), pubescent wheatgrass (*Elytrigia intermedia* L.) and perennial rye (*Lolium perenne* L.) mixes] provided superior weed control, were easy to establish, and led to no detectable grapevine water stress. Other research has indicated cover crops may compete with grapevines, thereby impairing grapevine productivity and fruit quality. For example, increasing coverage of grass cover crops was noted to decrease grapevine root growth in France (Morlat and Jacquet 2003). In California, Ingels et al. (2005) found reduced pruning weights and petiole nitrogen content in grapevines intercropped with native grasses, while no yield differences were detected. Wheeler et al. (2005) also observed reduced pruning weights and petiole nitrogen content in a New Zealand vineyard with permanent stands of intercropped chicory (*Chicorium intybus* L.). Yet, competition imposed by chicory improved wine-sensory attributes. Similarly, Monteiro and Lopes (2007) found permanent intercroppings of grass and legume mixes in a Portuguese vineyard reduced grapevine vegetative growth, but had no effect on yields. Monteiro and Lopes (2007) also found grass and legume mixes had favorable effects on fruit quality, as measured in increased anthocyanins and phenolic content.

Current research suggests plant competition imposed by living cover crops may have favorable effects on grapevine production within a particular region. Tesic et al. (2007)

investigated the effects of partial and complete groundcovers of resident vegetation within hot/semiarid and mild/semihumid climates of Australia. Competition imposed by increased groundcover altered grapevine canopy structure, as well as decreased petiole nutrient status, vegetative growth, fruit yield, and berry weight. Yet, effects of groundcover in the mild/semihumid climate, where moisture was less limiting, were minimal. In fact, results similar to those of Tesic et al. suggest groundcovers represent a way to control overly vigorous grapevines, which is often an undesirable feature of grapevine growth in locations with fertile soils and excessive moisture (Giese et al. 2008; Monteiro and Lopes 2007; Sicher et al. 1995; Wheeler et al. 2008). For example, altered canopy structure from reduced vegetative growth imposed by cover crops can increase exposure of fruit clusters. Increased light exposure has been found to facilitate ripening and lead to higher concentrations of desirable anthocyanins and phenolics (Dokoozlian and Kliewer 1996).

Vineyard floor management practices, such as cover crop implementation, are recognized to influence yield, fruit composition, and wine quality (Giese et al. 2008; Jackson and Lombard, 1993; Mackenzie and Christy 2005; Malusá et al. 2004; Morlat and Jacquet 2003; Rodriguez-Lovelle et al. 2000a; Rodriguez-Lovelle et al. 2000b; Wheeler et al. 2008). Water stress, which may be imposed by plant competition, can drastically impair grapevine productivity and alter fruit composition (Brown et al. 2001; Morlat and Jacquet 2003; Reynolds et al. 2007; Shellie 2006; Tesic et al. 2007). Contrary to common belief, physiological stress imposed by water competition does not necessarily improve fruit composition and subsequent wine quality. Under varying irrigation regimes within an Ontario vineyard, Reynolds et al. (2007) found fruit from irrigated treatments had overall higher yields, soluble solids concentrations, and favorable wine sensory attributes when compared to fruit from nonirrigated and early irrigation cut-off treatments. Management practices that increase organic matter input in soils may also have detrimental effects on fruit and wine quality. A 28-year experiment in France revealed that high rates of organic amendments lead to delayed fruit ripening and decreased soluble solids concentrations, anthocyanins, and tannins, as well as undesirable herbaceous odors in fermented juice (Morlat and Symoneaux 2008).

As demonstrated by the aforementioned investigations, vineyard floor management should be approached holistically after consideration of potential effects within a particular vineyard and winery. In Iowa, Dilley's (2007) research with creeping red fescue (*Festuca rubra* L. 'Pennlawn') grown under the trellis in an established vineyard suggested living mulches may be an effective method of weed control that promotes soil quality within the Midwest. However, Dilley's studies did not address the concern that living mulches may compete excessively with grapevines for water and nutrients, consequently compromising grapevine yield and fruit quality. With grapevine roots serving as major storage organs for carbohydrates and nutrients, stress induced by competition may adversely impact the sequestration of these reserves and subsequent grapevine growth aided by these reserves (Bates et al. 2002; Morlat and Jacquet 2003).

With the expansion of the Midwest grape and wine industry, further research on localized vineyard floor management practices and their long-term effects is needed for the sustainable development of this revitalized industry. Knowledge of management practices influence on grapevine growth, development, and fruit quality within this unique grape-growing region is in its infancy. Information on how newly introduced cold-climate cultivars respond to management practices is also limited, collectively reflecting a need for investigation. Combined with these needs for investigation, dissemination of research results is essential to elevate grower knowledge and awareness of sustainable land management, thereby ensuring the success of this new and promising industry.

Literature Cited

Bates, T.R., R.M. Dunst, and P. Joy. 2002. Seasonal dry matter, starch, and nutrient distribution in 'Concord' grapevine roots. HortScience. 37(1):313-316.

Bezdicek, D.F., R.I. Papendick, and R. Lal. 1996. Introduction: Importance of Soil Quality to Health and Sustainable Landscape Management, pp. 1-8. In: J.W. Doran and A.J. Jones (eds.). Methods for assessing soil quality. SSSA Special Publication 49. Soil Sci. Soc. Amer., Inc., Madison, WI.

Blair, J.M., P.J. Bohlen, and D.W. Freckman. 1996. Soil Invertebrates as Indicators of Soil Quality, pp. 273-291. In: J.W. Doran and A.J. Jones (eds.). Methods for assessing soil quality. SSSA Special Publication 49. Soil Sci. Soc. Amer., Inc., Madison, WI.

Brown, M.V., D.C. Ferree, D.M. Scurlock, and G. Sigel. 2001. Impact of soil drainage on growth, productivity, and fruit composition of 'Chambourcin' and 'Pino Gris' grapevines. HortTechnology. 11(2):272-276.

Chiras, D.D., J.P. Reganold, and O.S. Owen. 2002. Soil Conservation and Sustainable Agriculture, pp. 134-160. In: Natural Resource Conservation: Management for a Sustainable Future (8^{th} ed.). Prentice Hall. Upper Saddle River, NJ.

Delate, K. and H. Friedrich. 2004. Organic apple and grape performance in the Midwestern U.S. Acta Hort. 638:309-320.

Derr, J.F. 2008. Vineyard Weed Management, pp. 262-271. In: T. Wolf (ed.). Wine Grape Production Guide for Eastern North America. Pub. NRAES-145. Virginia Technical University. Natural Resource, Agriculture, and Engineering Service (NRAES) Cooperative Extension, Ithaca, NY.

Dick, R.P., D.P. Breakwell, and R.F. Turco. 1996. Soil Enzyme Activities and Biodiversity Measurements as Integrative Microbiological Indicators, pp. 247-271. In: J.W. Doran and A.J. Jones (eds.). Methods for assessing soil quality. SSSA Special Publication 49. Soil Sci. Soc. Amer., Inc., Madison, WI.

Dilley, C.A. 2007. Soil quality in strawberry and vineyard agroecosystems maintained under conventional and alternative weed management systems. PhD Diss., Dept. of Horticulture, Iowa State Univ., Ames. (Diss. p. 126).

Dokoozlian, N.K and W.M. Kliewer. 1996. Influence of light on grape berry growth and composition varies during fruit development. J. Amer. Soc. Hort. Sci. 121(5): 869-874.

Doran, J.W. and A.J. Jones (eds.). 1996. Methods for Assessing Soil Quality. SSSA Special Publication 49. Soil Sci. Soc. Amer., Inc., Madison, WI.

Elmore, C. 1996. A reintroduction to integrated weed management. Weed Sci. 44:409-412.

Ferree, D.C. and J.G. Streeter. 2004. Response of container-grown grapevines to soil compaction. HortScience. 39(6):1250-1254.

Gartner, W. and B. Tuck. 2008. The economic contribution of grape growers and wineries to the state of Minnesota. Univ. of Minn. p. 14. http://www.mngrapes.org/.

Giese, W.G., M. Kelly, T.K. Wolf. 2008. Effect of root pruning and groundcover on vegetative growth and fruit composition of Cabernet Sauvignon grapevines. Am. J. Enol. Vitic. 59(1):110A (Abstr.).

Glover, J.D., J.P. Reganold, and R.K. Andrews. 2000. Systematic method for rating soil quality of conventional, organic, and integrated apple orchards in Washington state. Agricult. Ecosys. Environ. 80:29-45.

Griffin, J.J., W.R. Reid, and D.J. Bremer. 2007. Turf species affects establishment and growth of redbud and pecan. HortScience. 42(2):267-271.

Hartwig, N.L. and H.U. Ammon. 2002. Cover crops and living mulches. Weed Sci. 50(6):688-699.

Hostetler, G.L., I.A. Merwin, M.G. Brown, and O. Padilla-Zakour. 2007. Influence of undervine floor management on weed competition, vine nutrition, and yields of Pinot noir. Am. J. Enol. Vitic. 58:421-430.

Ingles, C.A. 1992. Sustainable agriculture and grape production. Am. J. Enol. Vitic. 43:296-298.

Ingles, C.A., K.M. Scow, D.A. Whisson, and R.E. Drenovsky. 2005. Effects of cover crops on grapevines, yield, juice composition, soil microbial ecology, and gopher activity. Am. J. Enol. Vitic. 56:19-29.

Jackson, D.I. and P.B. Lombard. 1993. Environmental and management practices affecting grape composition and wine quality-A review. Am. J. Enol. Vitic. 44(4):409-430.

Karlen, D.L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil quality: A concept, definition, and framework for evaluation (a guest editorial). Soil Sci. Soc. Amer. J. 61:4-10.

Lal, R., T.M. Sobecki, T. Iivari, and J.M. Kimble. 2004. Water and wind erosion on U.S. cropland, pp. 109-130. In: Soil degradation in the United States: extent, severity, and trends. Lewis Publishers, Boca Raton, FL.

Leonard, O.A. and L.A. Lider. 1961. Studies of Monuron, Diuron, Simazine, and Atrazine on weed control, grape quality, and injury to vines. Am. J. Enol. Vitic. 12(2):69-80.

Mackenzie, D.E. and A.G. Christy. 2005. The role of soil chemistry in wine grape quality and sustainable soil management in vineyards. Water Sci. Technol. 51(1):27-37.

Malusá, E., E. Laurenti, E. Ghibaudi, and L. Rolle. 2004. Influence of organic and conventional management on yield and composition of grape cv. 'Grignolino.' Acta Hort. 640:135-141.

Merwin, I.A. and M.P. Pritts. 1993. Are modern fruit production systems sustainable? HortTechnology. 3(2):128-136.

Merwin, I.A., W.C. Stiles, and H.M. Van Es. 1994. Orchard groundcover management, impacts on soil physical properties. J. Amer. Soc. Hort. Sci. 119(2):216-222.

Midwest Grape and Wine Industry Institute. 2008. Iowa State Univ. Ext. 21 Apr. 2010. http:///www.extension.iastate.edu/Wine/.

Monteiro, A. and C.M. Lopes. 2007. Influence of cover crop on water use and performance of vineyard in Mediterranean Portugal. Agric. Ecosyst. Environ. 121: 336-342.

Morlat, R. and R. Symoneaux. 2008. Long-term additions of organic amendments in a Loire valley vineyard on a calcareous sandy soil. III. Effects on fruit composition and chemical sensory characteristics of Cabernet franc wine. Am. J. Enol. Vitic. 59(4): 375-386.

Morlat, R. and A. Jacquet. 2003. Grapevine root system and soil characteristics in a vineyard maintained long-term with or without inward sward. Am. J. Enol. Vitic. 54:1-7.

Olmstead, M.A., R.L. Wample, S.L. Greene, and J.M. Terara. 2001. Evaluation of potential cover crops for inland Pacific northwest vineyards. Am. J. Enol. Vitic. 52(4):292-303.

Paine, L.K. and H. Harrison. 1993. The historical roots of living mulch and related practices. HortTechnology. 3(2):137-143.

Pimentel, D., H. Acquay, M. Biltonen, P. Rice, M. Silva, J. Nelson, V. Lipner, S. Giordano, A. Horowitz, and M. D'Amore. 1992. Environmental and economic costs of pesticide use. BioScience. 42(10):750-760.

Pimentel, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurtz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, and R. Blair. 1995. Environmental and economic costs of soil erosion and conservation benefits. Science. 267:1117-1123.

Pimentel, D., C. Wilson, C. McCullum, R. Huang, P. Dwen, J. Flack, Q. Tran, T. Saltman, and B. Cliff. 1997. Economic and environmental benefits of biodiversity. BioScience. 47(11):747-757.

Pirog, R. 2000 (revised 2002). Grape expectations: A food system perspective of redeveloping the Iowa grape industry. Leopold Center for Sustainable Agriculture. Iowa State Univ., Ames. p. 30.

Pool, R.M., R.M. Dunst, and A.N. Lakso. 1990. Comparison of sod, mulch, cultivation, and herbicide floor management practices for grape production in nonirrigated vineyards. J. Am. Soc. Hort. Sci. 115:872-877.

Read, P.E. 2004. Developing a grape and wine industry in a non-traditional region. Acta Hort. 652:493-496.

Reynolds, A.G., W.D. Lowrey, L. Tomek, J. Hakimi, and C. de Savigny. 2007. Influence of irrigation on vine performance, fruit composition, and wine quality of ‘Chardonnay’ in a cool, humid climate. Am. J. Enol. Vitic. 58:217-228.

Rodriguez-Lovelle, B., J.P. Soyer, and C. Morlot. 2000a. Incidence of permanent grass cover on grapevine phonological evolution and grape berry ripening. Acta Hort. 526:241-248.

Rodriguez-Lovelle, B., J.P. Soyer, and C. Morlot. 2000b. Nitrogen availability in vineyard soils according to soil management practices. Effects on vine. Acta Hort. 526:277-285.

Sandler, H.A., P.E. Brock II, J.E. Vanden Heuvel. 2009. Effects of three reflective mulches on yield and fruit composition of coastal New England wine grapes. Am. J. Enol. Vitic. 60(3):332-338.

Sanguankeo, P.P., R.G. Leon, and J. Malone. 2009. Impact of weed management practices on grapevine growth and yield components. Weed Sci. 57:103-107.

Shellie, K.C. 2006. Vine and berry response of Merlot (*Vitis vinifera* L.) to differential water stress. Am. J. Enol. Vitic. 57:514-518.

Shoemaker, B. and G. Campbell. 2007. The Illinois grape and wine industry: Its current size, 2006 production, and growth. Univ. Ill. at Urbana-Champaign. p. 21. http://www.illinoiswine.com/pdf/industry-report07.pdf.

Sicher, L., A. Dorigoni, and G. Stringari. 1995. Soil management effects on nutritional status and grapevine performance. Acta Hort. 383:73-82.

Smith, R., L. Bettiga, M. Cahn, K. Baumgartner, L.E. Jackson, and T. Bensen. 2008. Vineyard floor management affects soil, plant nutrition, and grapevine yield and soil quality. Calif. Agric. 62:184-190.

Stamatiadis, S., A. Liopa-Tsakalidi, L.M. Maniati, P. Karageorgou, and E. Natioti. 1996. A Comparative Study of Soil Quality in Two Vineyards Differing in Soil Management Practices, pp. 381-392. In: J.W. Doran and A.J. Jones (eds.). Methods for assessing soil quality. SSSA Special Publication 49. Soil Sci. Soc. Amer., Inc., Madison, WI.

Sylvia, D.M., J.J. Fuhrmann, P.G. Hartel, and D.A. Zuberer. 2005. Principles and Applications of Soil Microbiology. 2nd ed. Pearson Education, Inc., Upper Saddle River, NJ.

Tegtmeier, E.M. and M.D. Duffy. 2004. External costs of agricultural production in the United States. Int. J. Ag. Sust. 2(1):1-20.

Tesic, D., M. Keller, and R.J. Hutton. 2007. Influence of vineyard floor management practices on grapevine growth, yield, and fruit composition. Am. J. Enol. Vitic. 58:1-11.

United States Department of Agriculture (USDA). 1999. Soil quality test kit guide. U.S. Dept. Agric., Agric. Res. Serv., and Nat. Resources Cons. Serv.

van Es, H. 2008. Water in the soil: It affects grapevines in multiple ways. Am. J. Enol. Vitic. 59(1):114A (Abstr.).

van Huyssteen, L. 1988. Soil preparation and grapevine root distribution-A qualitative and quantitative assessment, pp. 1-15. In: The Grapevine Root and its Environment. Department of Agricultural and Water Supply. Vitic. Oenol. Res. Inst. Stellenbosch, South Africa.

Wheeler, J.M., B.H. Taylor, and B.G. Young. 2008. Grapevine response to groundcover management in a humid climate. Am. J. Enol. Vitic. 59(1):111A (Abstr.).

Wheeler, S.J., A.S. Black, and G.J. Pickering. 2005. Vineyard floor management improves wine quality in highly vigorous *Vitis vinifera* ‘Cabernet Sauvignon’ in New Zealand. New Zeal. J. Crop. Hort. 33:317-328.

White, M.L. 2009. Iowa Grape Expectations. Iowa State Univ. Ext. Pub. 21 Apr. 2010. http://www.extension.iastate.edu/Wine/Resources/iowasvineyardgrowth.htm.

White, M.L. and M.R. Dharmadhikari. 2008. The Iowa boom includes wine. Wine east: News of grapes and wine in eastern north America. 36(1):12-55.

White, R.E. 2003. Soil and the Environment, pp. 3-26. In: Soils for Fine Wines. Oxford University Press, Inc., New York, NY.

Wisler, G.C. and R.F. Norris. 2005. Interactions between weeds and cultivated plants as related to management of plant pathogens. Sym. Weed Sci. 53:914-917.

Wolf, T.K. 2008. Crop Yield Estimation and Crop Management, pp. 135-168. In: T. Wolf (ed.). Wine Grape Production Guide for Eastern North America. Pub. NRAES-145. Virginia Technical University. Natural Resource, Agriculture, and Engineering Service (NRAES) Cooperative Extension, Ithaca, NY.

United States Department of Agriculture (USDA). 2008. Iowa Agricultural Overview. National Agricultural Statistics Service (NASS). 15 March 2010. http://www.nass.usda.gov/.

CHAPTER 2. MULCHES REDUCE WEEDS, MAINTAIN YIELD, AND PROMOTE SOIL QUALITY IN A MIDWESTERN VINEYARD

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Key words. vineyard floor management, living mulch, cover crops, sustainable viticulture, continental climate viticulture, fluorescein diacetate (FDA)

Abstract

Weeds reduce vineyard productivity by competing with grapevines for water and nutrients. To manage weeds, growers commonly apply herbicides and/or cultivate, which compromises soil quality. With the expansion of continental climate viticulture, such as in the Midwest, there is a need for sustainable weed management strategies that maintain grapevine productivity, fruit quality, and soil quality. Our objective was to evaluate four weed management strategies in a midwestern vineyard. Data were collected from an established vineyard in Iowa with 'Maréchal Foch' grapevines (*Vitis rupestris* Scheele ×*vinifera* L.) planted in a randomized complete block design. Treatments were replicated four times and included: 1) cultivation, 2) herbicide application, 3) straw mulch, and 4) a living mulch of creeping red fescue (*Festuca rubra* L. 'Pennlawn'). Weed control, grapevine productivity, fruit quality, and soil quality were measured in 2008 and 2009. Straw and living mulches controlled weed populations, whereas none of the treatments affected grapevine yield. Dormant cane pruning weights and fruit quality were lowest in cultivated and straw mulch plots, respectively. Water-filled pore space and water content were greater in mulched plots, while infiltration was fastest. No differences in chemical soil quality attributes were observed. Although earthworm populations were greater in straw mulch plots, no differences in soil enzymatic activity were found. Our results demonstrate straw and living mulches reduce weed populations, maintain grapevine productivity, improve several indicators of soil quality, and are viable weed management strategies for continental climate viticulture.

Introduction

The historically important midwestern grape and wine industry is being revitalized. For example, Iowa was the sixth-largest grape producer in the United States in 1919 (White and Dharmadhikari 2008). Prohibition, subsidies for agronomic crops, the introduction of phenoxy herbicides that damage grapevines, and the Armistice Day Freeze of 1940 contributed to declines in grape production. Since the 1990s, production has expanded due to recent interest in local and diversified agricultural systems. Production also has increased within adjacent states, illustrating continental climate viticulture is expanding (Gartner and Tuck 2008; Shoemaker and Campbell 2007). As the grape industry reemerges, it is important to encourage sustainable land management practices that are environmentally sound, economically viable, and socially responsible (Ingles 1992). This entails implementation of weed management practices that control weeds, promote grapevine productivity and fruit quality, and maintain soil quality.

Weeds compromise crop productivity through competition for resources including water, nutrients, and light. Weeds also can harbor and vector plant pests and pathogens (Wisler and Norris 2005). Unabated weeds threaten grapevine performance and productivity, particularly in organic vineyards where herbicide use is restricted (Delate and

Friedrich 2004). Conventional weed management for continental climate viticulture entails pre- and post-emergent herbicide applications and/or mechanical cultivation underneath vineyard rows, while permanent vegetative groundcovers are maintained between rows. The short-term effectiveness of these techniques has enabled growers to cultivate grapes. However, questions regarding the long-term impacts of these practices on grapevine productivity and soil quality remain unanswered.

Soil quality is defined as “the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and to support human health and habitation” (Karlen et al. 1997). Evaluations of soil quality emphasize consideration of chemical, physical, and biological properties of soil (USDA 1999). Conventional practices, such as maintaining bare soil through continual herbicide use and/or cultivation, lessen soil quality due to reduced organic matter and erosion. Cultivation and/or herbicide applications reduce vegetative groundcover and subsequent organic-matter input. Erosion and loss of soil structure are thereby exacerbated, while nutrient- and water-holding capacity, infiltration, and biological activity are reduced (Glover et al. 2000; Merwin et al. 1994; Smith et al. 2008). Excessive use and/or mismanagement of agrichemicals, such as herbicides, also may lead to accidental exposure to applicators and field workers, residuals and runoff, decreases in nontarget and/or beneficial-organism populations, and evolved resistance in target-organism populations (Pimentel et al. 1992).

Living mulches are vegetative groundcovers maintained as companion crops underneath or between vineyard rows. Benefits of living mulches include reductions in weed populations, soil erosion, and agrichemical runoff (Hartwig and Ammon 2002).

Consequently, soil organic matter content, soil structure, soil fertility, and crop productivity are improved. Despite the capability of living mulches to improve soil quality, information on their competitive effects on the growth and development of grapevines and on fruit quality is conflicting. Ingels et al. (2005) found reduced pruning weights and petiole nitrogen content in California grapevines intercropped with native grasses, but no yield differences were detected. Elsewhere in California, yield reductions exceeding 40% have been reported when grapevines were intercropped with native plant species (Sanguankeo et al. 2009). Plantings of grasses and legumes in Portugal had no effect on yield, reduced grapevine vegetative growth, and improved fruit quality, as measured by increased phenols and anthocyanins (Monteiro and Lopes 2007).

Our objective was to evaluate the effects of four weed management strategies on weed control, grapevine performance, and soil quality in an established midwestern vineyard. Few integrated studies on vineyard weed management and soil quality have been conducted within grape-growing regions subject to continental climates and with rain-fed agriculture, such as the Midwest. Compared to other grape-growing regions of the world, the climate and soils of these environments presents a unique set of vineyard management challenges in need of optimization. The long-term sustainability of these revitalized industries largely depends on the implementation of weed control strategies that maintain both grapevine performance and soil quality within these unique grape-growing regions of the world.

Materials and Methods

Vineyard site

The experiment was conducted from 2007 to 2009 in a vineyard established in 1985 at the Iowa State University Horticulture Research Station near Ames, IA (latitude 42˚06'29"N; longitude 93˚35' 09"W). Statewide climate is continental and the growing season extends from Mar. to Oct. Temperature and precipitation data was retrieved from the Iowa Environmental Mesonet website (http://mesonet.agron.iastate.edu/). For the 2007, 2008, and 2009 growing seasons, total precipitation was 880, 1140, and 850 mm, respectively. The average high and low air temperatures for the 2007 growing season were 23 and 12 ^{o}C, respectively. The average high was 21 ^{o}C in 2008 and 19 ^{o}C in 2009. The average low was 9 ^{o}C for both the 2008 and 2009 growing seasons. Soil was a Clarion loam on a 2 to 9% slope. Clarion loams are formed from superglacial till. These soils are characterized as fine-loamy, mixed, superactive, mesic Typic Hapludolls with moderately good drainage and a high available water-holding capacity (USDA 1984). The vineyard site was untiled with rows in a north-south orientation. All vines were trained to a six-cane kniffen and spaced 1.8 m within the row and 2.7 m between rows. From 1985 to 2003, herbicide applications were used to control weeds within a 0.9-m-wide area underneath the vineyard row, while a 1.8-m-wide strip of Kentucky bluegrass (*Poa pratensis* L.) and resident vegetation was maintained between rows. Fertilizer and pesticide applications for disease and insect control followed extension recommendations (Dami et al. 2005; Bordelon et al. 2008).

Experimental design

The experimental design was a randomized complete block with four treatments replicated four times. Sixteen plots, each 7.3 × 0.9 m, were treated as experimental units. Observations were made on four grapevines and averaged for each unit. Each plot received one of the following weed management treatments applied within a 0.9-m-wide area underneath the vineyard row: 1) mechanical cultivation, 2) herbicide application, 3) straw mulch, and 4) living mulch. Cultivation was performed during May, June, and July with a hand-held tiller. Soils were tilled to a depth of approximately 5 cm. Herbicide applications followed recommendations prescribed by the Midwest Commercial Small Fruit and Grape Spray Guide (Bordelon et al. 2008). After weed data collection, glyphosate was applied at a rate of 1.1 kg a.i./ha. A mulch of oat straw was initially applied in 2004 at a rate of 13.6 t/ha and to a depth of approximately 10 cm to suppress germination and growth of weed seeds. Mulch was reapplied on a spot-treatment basis in spring 2007 and 2009; mulch was not needed in 2008 because it sufficiently covered the ground. A groundcover of shade-tolerant creeping red fescue (*Festuca rubra* L. 'Pennlawn') served as the living mulch treatment and was seeded 25 Sept. 2003 at 19.5 g/m^2. The fescue was overhead-irrigated until establishment and was not mowed nor over-seeded throughout the experiment.

Grapevine sampling

The interspecific hybrid cultivar Maréchal Foch (*Vitis rupestris* Scheele ×*vinifera* L.) was used in the experiment. Grapevines were balance pruned with a 30 + 10 bud adjustment in March and April of 2008 and 2009, respectively. During pruning, weights of dormant canes were collected to measure grapevine vegetative growth. No cluster thinning was done. In Aug. 2008 and Aug. 2009, 150 to 200 petioles were collected per plot. Petioles were analyzed for nutrient content by A & L Great Lakes Laboratory, Inc., Fort Wayne, IN.

Fruit harvest occurred on 9 Sept. 2008 and 8 Sept. 2009. At harvest, yield data, including per-grapevine weight, cluster number, and average cluster weight were determined. Samples of 50 berries were collected randomly from grapevine clusters within each experimental plot and frozen for subsequent fruit quality analyses. Mean berry weight, percentage soluble solids [SSC(%)/Brix], initial pH, and titratable acidity were determined after thawing (Amerine and Ough 1980).

Weed sampling

Weed control was measured during 2008 and 2009 in May, June, July, and Aug. via visual estimates of percentage weed cover and total monocot and dicot shoot biomass. Visual estimates were collected from three randomly placed 0.25 m^2 quadrats per plot. All weeds within each quadrat were harvested, separated as a monocot or dicot, and processed. Processing entailed root removal and drying of shoots at 67 ºC for 72 h before biomass was determined.

Soil sampling

Soil samples were collected on 29 Sept. 2007, 4 Nov. 2008, and 5 Nov. 2009. Composite samples representative of each experimental unit were collected from 12 randomized soil cores that were 15.2 × 3.1 cm. Cores were divided into subsamples at 0- to 7.6-cm and 7.6- to 15.2-cm depths. Within 24 h after collection, soils were passed through an 8-mm sieve and allowed to air-dry at 22 ± 1 ºC before being stored in a 3 ± 1 ºC cooler for subsequent analyses.

Soil-quality analyses entailed measurements of chemical, physical, and biological soil properties. Chemical properties measured were pH, percentage organic matter, total organic carbon (C) and nitrogen (N,) inorganic mineral nitrogen (NH_3-N and NO_3-N), Bray-1 phosphorus (P), and cations of potassium (K), magnesium (Mg), and calcium (Ca). Soil pH was measured with a HANNA H19813 meter (HANNA Instruments®, Woonsocket, RI, USA) by using a 1:1 dilution of deionized water and soil (USDA 1999). Percentage organic matter and total C and N were determined by combustion analysis (Combs and Nathan 1998) in an elemental analyzer (Haake Buchler Instruments, Paterson, NJ, USA). Inorganic mineral N was determined colorimetricallly by the cadmium reduction method (Gelderman and Beegle 1998). Phosphorus was extracted according to the procedure outlined by Frank et al. (1998). Potassium, Mg, and Ca were assayed using a Mehlich-3 extraction (Warncke and Brown 1998).

Measured physical soil properties included bulk density, total porosity, water-filled pore space, gravimetric and volumetric water content, flooded/ponded initial infiltration rate, and stable aggregate content. Gravimetric water content was determined immediately after fall soil collection by oven-drying field-moist soil for 24 h at 105 ºC (USDA 1999). Bulk density and infiltration measurements were collected only in 2009 due to excessively wet soil conditions in previous years. Soils from measures of bulk density were used to calculate volumetric soil water content by drying 60 cm^3 of field-moist soil for 24 h at 105 ºC (USDA 1999). Total and water-filled pore spaces were calculated from measures of bulk density and water content. Infiltration rate was measured according to the USDA (1999). Stable aggregate content was measured according to the procedure described by Patton et al. (2001).

Potential soil enzymatic activity was quantified via fluorescein diacetate (FDA) hydrolysis (Green et al. 2006). Esterases, lipases, and proteases produced by soil organisms hydrolyze FDA-containing substrates and produce fluorescein. Fluorescein was quantified with a Spectronic 20D+ spectrophtometer (Spectronic Analytical Instruments, Leeds, UK) at 490 nm. After the 2009 growing season, earthworm populations were measured as another biological indicator of soil quality. Populations of horizontal-dwelling earthworms were enumerated by hand-sorting 25 cm^3 of surface soil (Blair et al. 1996).

Data analysis

All data were analyzed with Statistical Analysis System software using a mixed model (PROC MIXED) procedure and a least-squares mean (lsmeans) option (version 9.1; SAS Institute, Cary, NC). For tests of significance ($P \leq 0.05$), means were separated with a Tukey-Kramer adjustment for multiple comparisons.

Results

Grapevine growth and yield

Grapevine yield, cluster number, and average cluster weight were unaffected by treatments (Table 1). However, dormant cane pruning weights were 0.22, 0.23, and 0.36 kg/vine lower in cultivated compared to herbicide, living mulch, and straw plots, respectively. Reduced pruning weights were observed only in 2008. No treatment effects on plant nutrient content were observed (Appendix Tables 1).

Fruit quality

Berry weight was unaffected by treatment in 2008 and was greatest in living mulch plots in 2009 (Table 2). Percentage soluble solids was greatest in cultivation and herbicide plots in 2008, and lowest in straw mulch plots both years. Fruit from straw mulch plots had greater pH and lower titratable acidity when compared to all other treatments. Titratable acidity was greatest in living mulch plots both years.

Weed cover and biomass

Straw and living mulch controlled weeds. Percentage weed cover in straw mulch plots increased July 2008 and July 2009, which was predominately from monocots (Fig. 1, Table 3). Percentage weed cover and shoot biomass were consistently low in living mulch plots, particularly during May and July of both years (Fig. 1, Table 3). However, biomass of monocot weeds in Aug. 2009 increased in living mulch plots and was greater compared to all other treatments (Table 3).

Weed cover in herbicide-treated plots was less than 50% at all sampling dates except July 2008, during which there was an increase in dicot weeds (Fig. 1, Table 3). In July 2009, herbicide-treated plots had lower percentage weed cover and biomass than straw mulch plots (Fig. 1, Table 3). At all sampling dates, weed cover was greatest in cultivation plots (Fig. 1). In Aug. 2009, percentage weed cover and biomass in cultivation and herbicide plots were lowest compared to previous sampling dates within the year (Fig. 1, Table 3).

Soil quality

Excluding pH, there were no differences in chemical soil quality indicators (Appendix Tables 2 and 3). Soil pH was greatest in straw mulch plots at the 0- to 7.6-cm depth, whereas no differences were observed at the 7.6- to 15.2-cm depth. Bulk density and soil porosity were unaffected by weed management treatments (Table 4). Straw and living mulch plots had greater water-filled pore space, gravimetric and volumetric water content, and initial infiltration rates than cultivated and herbicide-treated plots. Initial infiltration was the same in straw and living mulch plots, whereas it was more than 20 times slower in herbicide plots. Differences in stable aggregate content and FDA hydrolysis were not detected (Appendix Tables 4 to 6). Earthworm populations were greatest in straw mulch plots, which had a mean population of 23 earthworms per 25 cm^3 of soil. Populations of earthworms were the same among the remaining treatments. Four, 2, and 2 earthworms per 25 cm^3 of soil were observed in the cultivation, herbicide-treated, and living mulch plots, respectively.

Discussion

To our knowledge, this research is the first integrated study on weed management and soil quality for vineyards subject to rain-fed continental climates, such as in the Midwest. Straw and living mulches of creeping red fescue are promising methods of weed control that promote soil quality. Compared to cultivation and herbicide application, both straw and living mulches provided superior weed control and had no effect on grapevine yield. Weed management practices did impact vegetative growth and fruit quality.

Mulches and cover crops provide effective alternatives to conventional weed management and enhance soil quality (Hartwig and Ammon 2002). However, previous studies show living groundcovers may have undesirable consequences on grapevine growth and development due to plant competition. Grapevines grown in dry climates are particularly susceptible to water competition, which can reduce vegetative growth, yield, and berry size (Ingels et al. 2005; Monteiro and Lopes 2007; Sanguankeo et al. 2009; Tesic et al. 2007). Despite previous findings, our study shows competition imposed by living mulches has no effect on grapevine growth, yield, and berry size (Tables 1 and 2). The continental climate of the Midwest is cooler and receives greater precipitation than many other grape-growing regions of the world. Moreover, the years in which the study was conducted were unusually wet, particularly in 2008 in which the vineyard experienced spring flooding. As a result of these climactic factors, competition for water is likely to be minimal under normal, drought-free conditions. Vegetative growth, measured by pruning weights, was reduced in cultivated plots (Table 1). This reduction may have been due to root destruction from cultivation, which can reduce shoot growth (Poni et al. 1992).

All fruit quality variables were within acceptable ranges. However, fruit derived from plots with straw mulch were less desirable due to reduced percentage soluble solids, increased pH, and less titratable acidity (Table 2). Environmental effects, such as excessive soil moisture, are known to impact grapevine phenology, fruit composition, and subsequent quality (Jones and Davis 2000). Cover provided by the straw mulch could have delayed fruit ripening by reducing evaporation from the soil, subsequently increasing soil moisture content. With increased soil moisture, the high specific heat capacity of water may have caused soil temperatures to warm more slowly in the spring, thereby delaying grapevine growth and development. Continued water uptake after véraison could have also delayed fruit maturation and lead to abnormal ripening. Delayed ripening is known to occur when grapevine water uptake is unlimited after véraison, whereas limited water uptake accelerates ripening (Winkler et al. 1974). Wade et al. (2004) also found fruit ripened faster and had optimal fruit quality when water deficits were imposed between fruit-set and véraison, whereas ripening was slower and quality was reduced under non-deficit soil moisture conditions. Water content was highest in straw mulched plots, which further supports the explanation that soil moisture was a factor in fruit ripening and quality (Table 4).

Berry weight was greater from fruit harvested from plots with a living mulch (Table 2). This observation conflicts with previous reports that competition imposed by vegetation results in smaller berry size and weight (Monteiro and Lopes 2007; Sanguankeo et al. 2009; Tesic et al. 2007). In fact, berry weight was smallest from grapevines grown with a straw mulch, which also had among the highest soil moisture content across all treatments (Tables 2 and 4). As previously mentioned, excessive soil moisture in straw mulch plots is likely to have delayed grapevine growth and fruit ripening, particularly after véraison, which would also explain the reduction of berry size and weight. Sufficient soil moisture and nutrients are likely to have mitigated any existing competition between the grapevines and living mulch, thereby explaining the lack of size reduction. Moreover, optimal soil moisture in the living mulch plots during key phenological stages in grapevine development could have favored fruit ripening. Reynolds et al. (2007) found grapevines grown with minimal water stress in Ontario had increased berry size. In our study, the living mulch treatments had greater soil-water content than the cultivation and herbicide-treated plots (Table 4). Moreover, grapevine nutrient content and soil chemical analyses revealed no treatment differences. Together, these observations support the explanation that minimal water stress and nutrient competition resulted in larger berry size (Table 4). Beneficial rhizosphere effects from the living mulch also could have favored berry growth and development (Menge et al. 1983).

Consistent with previous findings, straw and living mulches reduced weed populations (Fig. 1 and Table 3) (Hartwig and Ammon 2002; Ingels et al. 2005). By maintaining a permanent groundcover, weed-seed germination and growth are inhibited, consequently reducing weed populations. In contrast, exposed soil provides a favorable environment for seed germination and growth, as reflected by the overall greater percentage weed cover and biomass observed in cultivated and herbicide-treated plots.

All physical soil quality indicators were within USDA-recommended ranges (USDA 1999). However, initial infiltration was improved with mulches (Table 4). Mulches increase soil organic matter content, which stabilizes soil aggregates and reduces their breakdown, decreases surface crusting, and enhances infiltration (Sikora and Stott 1996). Surface crusting (visual observation) and slower initial infiltration rates were observed in cultivation and herbicide-treated plots, demonstrating the beneficial effects mulches have on physical soil properties (Table 4). While few differences in chemical soil properties were observed, continued monitoring is recommended because conventional testing procedures may not detect differences for several years (Sikora and Stott 1996).

Additional evaluation of biological soil properties is also advised. Because soil biological activity is largely dependent on carbon-source availability, the lack of differences in soil chemistry (especially carbon) may explain why differences in enzymatic activity were not observed (Dick et al. 1996). Furthermore, the methodology of measuring potential enzymatic activity may not be robust enough and in need of optimization. Earthworm populations were greater in straw mulch plots, which is consistent with previous findings (Thomson and Hoffmann 2007). Increased populations were expected due to the surface applications of straw, which is ingested by earthworms. Additionally, by providing a barrier between the ambient air and soil, the straw mulch created an environment ideal for earthworms, which are unable to regulate body temperature and water content. Earthworms are valued members of the soil ecological community due to their role in decomposition of organic matter, soil mixing, promotion of soil structure, and stimulation of biological activity. Due to the beneficial effects of earthworm activity, their increase in numbers is an indicator of improved soil quality.

Conclusion

This study provides information on weed management and soil quality for the unique and rapidly expanding industry of continental climate viticulture. Despite concerns of competition, this study demonstrates that living mulches control weed populations, maintain grapevine yield and fruit quality, and enhance soil quality. Straw mulch had similar effects on weed control, grapevine yield, and soil quality, but slightly reduced fruit quality. Although competition between the living mulches and grapevines was not detected, it should be noted that the conditions in which the study was conducted were abnormally wet. Therefore, results may not reflect how grapevines would respond to living mulches under normal climactic conditions. Continued monitoring and evaluation of the long-term effects will provide additional information regarding the practicality of mulches within continental climate vineyards. Future studies should also evaluate the effects of mulches on wine-sensory attributes, as well as the economic implications of various weed management systems. Our study suggests mulches contribute to the sustainability of vineyard operations and are a viable option for sustainable weed management for continental climate viticulture.

Literature Cited

Amerine, M.A. and C.S. Ough. 1980. Methods for Analysis of Musts and Wines. John Wiley and Sons. New York, NY.

Blair, J.M., P.J. Bohlen, and D.W. Freckman. 1996. Soil invertebrates as indicators of soil quality. *In* Methods for Assessing Soil Quality. J.W. Doran and A.J. Jones (eds.), pp. 273-291. SSSA Special Publication 49. Soil Sci. Soc. Amer., Madison, WI.

Bordelon, B., M. Ellis, and R. Weinzierl (eds.). 2008. Midwest Commercial Small Fruit and Grape Spray Guide 2008. Purdue Univ., West Lafayette, Ind.

Combs, S.M. and M.V. Nathan. 1998. Soil organic matter. *In* Recommended Chemical Soil Test Procedures for the North Central Region. J.R. Brown (ed.), pp. 53-58. North Central Regional Research Publication No. 221. Missouri Agricultural Experiment Station. Columbia, MO.

Dami, I., B. Bordelon, D.C. Ferree, M. Brown, M.A. Ellis, R.N. Williams, and D. Doohan. 2005. Midwest grape production guide. Ohio State Univ. Ext. Bul. 919-05.

Delate, K. and H. Friedrich. 2004. Organic apple and grape performance in the midwestern U.S. Acta Hort. 638:309-320.

Dick, R.P., D.P. Breakwell, and R.F. Turco. 1996. Soil enzyme activities and biodiversity measurements as integrative microbiological indicators. *In* Methods for Assessing Soil Quality. J.W. Doran and A.J. Jones (eds.), pp. 247-271. SSSA Special Publication 49. Soil Sci. Soc. Amer., Madison, WI.

Frank, K., D. Beegle, J. Denning. 1998. Phosphorus. *In* Recommended Chemical Soil Test Procedures for the North Central Region. J.R. Brown (ed.), pp. 21-29. North

Central Regional Research Publication No. 221. Missouri Agricultural Experiment Station. Columbia, MO.

Gartner, W. and B. Tuck. 2008. The economic contribution of grape growers and wineries to the state of Minnesota. Univ. of Minn. Minneapolis-St. Paul, MN.

Gelderman, R.H. and D. Beegle 1998. Nitrate-Nitrogen. *In* Recommended Chemical Soil Test Procedures for the North Central Region. J.R. Brown (ed.), pp. 17-20. North Central Regional Research Publication No. 221. Missouri Agricultural Experiment Station. Columbia, MO.

Glover, J.D., J.P. Reganold, and R.K. Andrews. 2000. Systematic method for rating soil quality of conventional, organic, and integrated apple orchards in Washington state. Agricult. Ecosys. Environ. 80:29-45.

Green, V.S., D.E. Scott, and M. Diack. 2006. Assay for fluorescein diacetate hydrolytic activity: Optimization for soil samples. Soil Biol. Biochem. 38:693-701.

Hartwig, N.L. and H.U. Ammon. 2002. Cover crops and living mulches. Weed Sci. 50:688-699.

Ingles, C.A. 1992. Sustainable agriculture and grape production. Am. J. Enol. Vitic. 43:296-298.

Ingles, C.A., K.M. Scow, D.A. Whisson, and R.E. Drenovsky. 2005. Effects of cover crops on grapevines, yield, juice composition, soil microbial ecology, and gopher activity. Am. J. Enol. Vitic. 56:19-29.

Jones, G.V. and R.E. Davis. 2000. Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. Am. J. Enol. Vitic. 51:249-261.

Karlen, D.L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Sci. Soc. Amer. J. 61:4-10.

Menge, J.A., D.J. Raski, L.A. Lider, E.L.V. Johnson, and N.O. Jones. 1983. Interactions between mycorrhizal fungi, soil fumigation, and growth of grapes in California. Am. J. Enol. Vitic. 34:117-121.

Merwin, I.A., W.C. Stiles, and H.M. Van Es. 1994. Orchard groundcover management, impacts on soil physical properties. J. Am. Soc. Hort. Sci. 119:216-222.

Monteiro, A. and C.M. Lopes. 2007. Influence of cover crop on water use and performance of vineyard in Mediterranean Portugal. Agric. Ecosyst. Environ. 121:336-342.

Patton, J.J., L. Burras, M.E. Konen, and N.E. Molstad. 2001. An accurate and inexpensive apparatus and method for teaching and measuring stable aggregate content of soils. J. Nat. Resour. Life Sci. Educ. 30:84-88.

Pimentel, D., H. Acquay, M. Biltonen, P. Rice, M. Silva, J. Nelson, V. Lipner, S. Giordano, A. Horowitz, and M. D'Amore. 1992. Environmental and economic costs of pesticide use. BioScience 42:750-760.

Poni, S., M. Tagliavini, D. Scudellari, and M. Toselli. 1992. Influence of root pruning and water stress on growth and physiological factors of potted apple, grape, peach and pear trees. Sci. Hort. 52:223-236.

Reynolds, A.G., W.D. Lowrey, L. Tomek, J. Hakimi, and C. de Savigny. 2007. Influence of irrigation on vine performance, fruit composition, and wine quality of Chardonnay in a cool, humid climate. Am. J. Enol. Vitic. 58:217-228.

Sanguankeo, P.P., R.G. Leon, and J. Malone. 2009. Impact of weed management practices on grapevine growth and yield components. Weed Sci. 57:103-107.

Shoemaker, B. and G. Campbell. 2007. The Illinois grape and wine industry: Its current size, 2006 production, and growth. Univ. Ill. at Urbana-Champaign. Urbana, IL.

Sikora, L.J. and D.E. Stott. 1996. Soil organic carbon and nitrogen. *In* Methods for Assessing Soil Quality. J.W. Doran and A.J. Jones (eds.), pp. 157-167. SSSA Special Publication 49. Soil Sci. Soc. Amer., Madison, WI.

Smith, R., L. Bettiga, M. Cahn, K. Baumgartner, L.E. Jackson, and T. Bensen. 2008. Vineyard floor management affects soil, plant nutrition, and grapevine yield and soil quality. Calif. Agric. 62:184-190.

Tesic, D., M. Keller, and R.J. Hutton. 2007. Influence of vineyard floor management practices on grapevine growth, yield, and fruit composition. Am. J. Enol. Vitic. 58:1-11.

Thomson, L.J. and A.A. Hoffmann. 2007. Effects of groundcover (straw and compost) on the abundance of natural enemies and macro invertebrates in vineyards. Agric. Forest Entomol. 9:173-179.

United States Department of Agriculture (USDA). 1984. Soil Survey of Story County, Iowa. Soil Conservation Service.

United States Department of Agriculture (USDA). 1999. Soil quality test kit guide. U.S. Dept. Agric., Agric. Res. Serv., and Nat. Resources Cons. Serv.

Wade, J., B. Holzapfel, K. Degaris, D. Williams, and M. Keller. 2004. Nitrogen and water management strategies for wine-grape quality. Acta Hort. 640:61-67.

Warncke, D. and J.R. Brown. 1998. Potassium and other basic cations. *In* Recommended Chemical Soil Test Procedures for the North Central Region. J.R. Brown (ed.), pp. 31-34. North Central Regional Research Publication No. 221. Missouri Agricultural Experiment Station. Columbia, MO.

White, M.L. and M.R. Dharmadhikari. 2008. The Iowa boom includes wine. Wine east: News of grapes and wine in eastern North America. 36:12-55.

Winkler, A.J., J.A. Cook, W.M. Kliewer, and L.A. Lider. 1974. Development and composition of grapes. *In* General Viticulture, pp. 138-196. Univ. of Calif. Press. Berkeley and Los Angeles, CA.

Wisler, G.C. and R.F. Norris. 2005. Interactions between weeds and cultivated plants as related to management of plant pathogens. Sym. Weed Sci. 53:914-917.

Table 1. Yield and growth of 'Maréchal Foch' grapevines under four weed management treatements in 2008 and 2009. Treatments were replicated four times in 16 plots. Observations were made on four grapevines per plot and averaged for each experimental unit.

	2008				2009			
Treatment	Yield (kg/vine)	Vine cluster no.	Avg cluster wt (g)	Pruning wt (kg/vine)	Yield (kg/vine)	Vine cluster no.	Avg cluster wt (g)	Pruning wt (kg/vine)
Cultivation	4.7 a[a]	59 a	77.5 a	0.24 a	7.4 a	111 a	66.7 a	0.7 a
Herbicide	5.2 a	63 a	89.5 a	0.46 ab	6.7 a	105 a	62.8 a	1.0 a
Living mulch	5.7 a	61 a	87.4 a	0.47 ab	7.0 a	108 a	64.9 a	1.0 a
Straw mulch	5.9 a	76 a	77.5 a	0.60 ab	6.7 a	116 a	58.6 a	1.2 a

[a]Means of four replications calculated from four grapevines per experimental unit, or plot, with 16 units total; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Table 2. Fruit quality of ‘Maréchal Foch’ grapevines under four weed management treatments in 2008 and 2009. Treatments were replicated four times in 16 plots. Observations were made on four grapevines per plot and averaged for each experimental unit.

	2008				2009			
Treatment	Berry wt (g)[a]	Brix[b]	pH	Titratable acidity (g/L)	Berry wt (g)	Brix	pH	Titratable acidity (g/L)
Cultivation	1.12 a[c]	20.6 bc	3.37 a	0.92 bc	1.08 bc	19.4 b	3.32 a	0.96 ab
Herbicide	1.14 a	20.7 cd	3.51 ab	0.90 bc	1.09 bc	18.9 b	3.42 ab	0.96 ab
Living mulch	1.15 a	20.1 a	3.43 ab	1.00 c	1.12 c	19.3 b	3.33 a	1.1 a
Straw mulch	1.07 a	19.7 a	3.56 bc	0.87 ab	1.02 ab	18.2 a	3.51 bc	0.85 bc

[a]Fruit quality variables calculated from a 50-berry sample.
[b]Percentage soluble solids concentration (%SSC).
[c]Means of four replications calculated from four grapevines per experimental unit, or plot, with 16 units total; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Table 3. Shoot biomass of monocot and dicot weeds collected from rows of 'Maréchal Foch' that received one of four weed management treatments in 2008 and 2009. Treatments were replicated four times in 16 plots. Percentage weed cover was calculated from averages of three 0.25-m^2 quadrats per plot.

	Dried weed shoot biomass (g)									
	2008				2009					
	May		July		May		July		Aug.	
Treatment	Monocot	Dicot	Monocot	Dicot	Monocot	Dicot	Monocot	Dicot	Monocot	Dicot
Cultivation	0.75 a[a]	3.23 ab	11.50 a	20.28 bc	8.90 a	16.75 b	19.00 bc	36.25 b	0.43 ab	1.14 a
Herbicide	0.10 a	0.68 ab	0 a	11.07 ab	0.94 a	2.78 a	0 a	3.66 a	0.02 a	1.55 a
Living mulch	0.04 a	0 a	0 a	0 a	0 a	0.80 a	0.50 a	0 a	2.71 c	0.06 a
Straw mulch	0.60 a	0.03 ab	8.67 a	1.78 a	0.60 a	0.38 a	10.72 ab	7.76 a	0.33 ab	1.30 a

[a]Values are means of 16 experimental units with four replications; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Table 4. Indicators of soil quality from vineyard soils receiving four weed management treatments in 2009. Treatments were replicated four times in 16 plots. Measurements of physical soil quality indicators were collected from three samples per plot and averaged for each experimental unit.

Treatment	Bulk density (g/cm)	Porosity (%)	Water-filled pore space (%)	Water content (%)	Volumetric water content (%)	Initial infiltration[a] (min)
Cultivation	1.29 a[b]	51.3 a	25.6 a	17 a	13 a	6.80 b
Herbicide	1.30 a	50.0 a	26.8 a	18 a	14 a	14.70 c
Living mulch	1.17 a	55.9 a	34.8 b	22 b	20 b	0.42 a
Straw mulch	1.28 a	51.7 a	45.3 c	30 c	24 b	0.59 a

[a]Time for 2.5 cm of water to infiltrate into soil.
[b]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

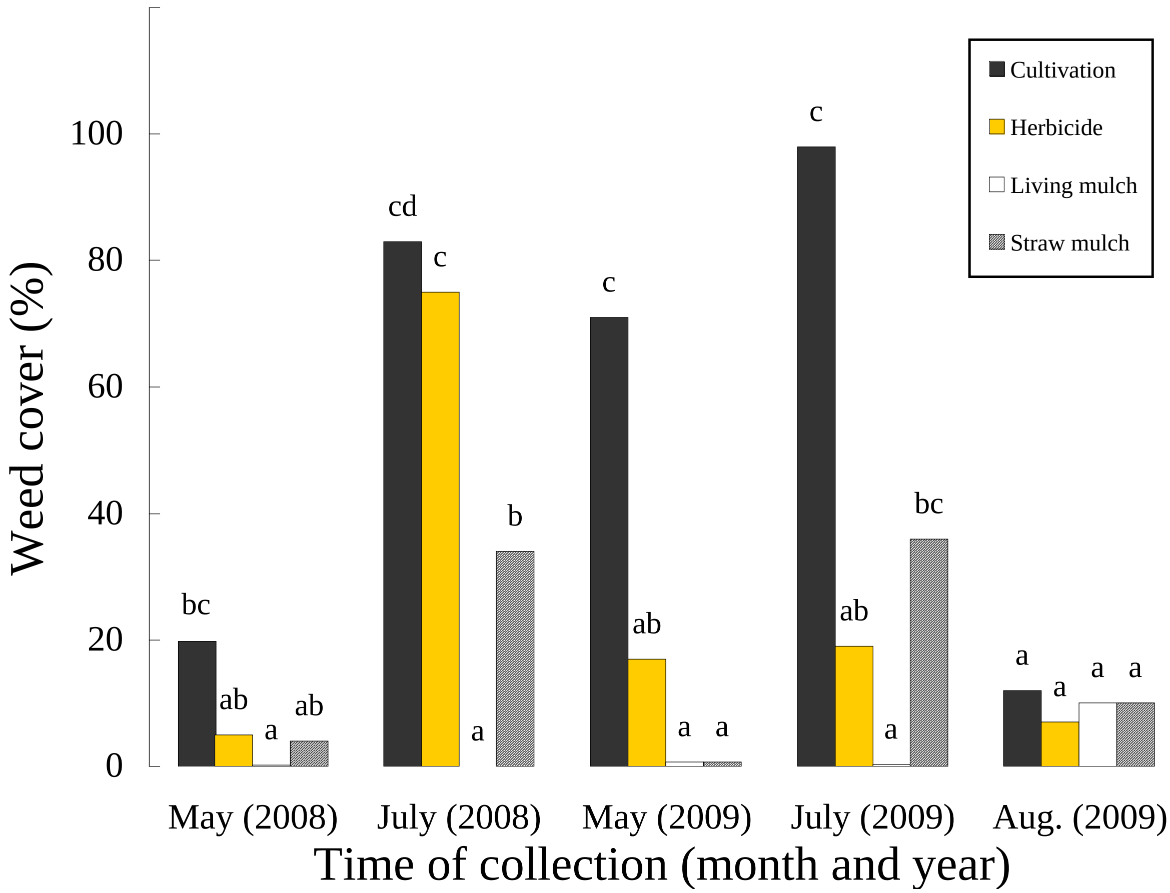

Fig. 1. Percentage weed cover estimated visually from rows of ‘Maréchal Foch’ receiving four weed-management treatments in 2008 and 2009. Treatments were replicated four times in 16 plots. Percentage weed cover was calculated from averages of three 0.2-m^2 quadrats per plot. Percentages with the same letter are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

CHAPTER 3. LIVING MULCHES MAINTAIN GRAPEVINE PERFORMANCE AND PROMOTE SOIL QUALITY IN A MIDWESTERN VINEYARD

A research note to be submitted to the *American Journal of Enology and Viticulture*

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Key words. vineyard floor management, living mulch, irrigation, competition, sustainable viticulture, fluorescein diacetate (FDA)

Abstract

Weeds reduce vineyard productivity by competing with grapevines for water and nutrients. To manage weeds, growers commonly apply herbicides and/or cultivate, which compromises soil quality. Sustainable weed management strategies are needed to maintain grapevine productivity, fruit quality, and soil quality within midwestern vineyards. Previous research suggests living mulches may provide a sustainable approach to vineyard weed management. Yet, information regarding the competitive effects of living mulches on grapevine growth and development is needed. The objective of this study was to evaluate the effects of living mulches, with and without irrigation, on grapevine growth and development within a midwestern vineyard. Data were collected from an established vineyard in Iowa with 'Reliance' and 'Swenson Red' grapevines (*Vitus labrusca* L.) planted in a randomized complete block design. Treatments were replicated eight times and included: 1) herbicide application without irrigation, 2) herbicide application with irrigation, 3) living mulch without irrigation, and 4) living mulch with irrigation. Living mulch was a mixture of shade-tolerant creeping red and Chewings fescue [*Festuca rubra* L. 'Foxy' and *F. rubra* var. *fallax* (Thuill.) Hack. 'Ambrose,' respectively]. Supplemental irrigation was

provided via drip irrigation and scheduling regimes were based on fescue evapotranspiration. Living mulches and irrigation had no consistent effect on grapevine growth and development, suggesting little-to-no competition existed between the grapevines and living mulches during the period in which the study was conducted. Unusually wet conditions during the period in which the study was conducted could have contributed to the observed lack of competition. When compared to both herbicide-treated plots, living mulches reduced weed populations and promoted several indicators of soil quality. Results demonstrate living mulches maintain grapevine performance, control weeds, and may be a viable alternative to vineyard weed management that promotes soil quality within the Midwest.

Introduction

The historically important midwestern grape and wine industry is being revitalized. Iowa was once the sixth-largest grape producer in the United States in 1919 (White and Dharmadhikari 2008). Prohibition, subsidies for agronomic crops, the introduction of phenoxy herbicides that damage grapevines, and the Armistice Day Freeze of 1940 contributed to a decline in Iowa's early grape industry. Since the 1990s, production has expanded due to recent interest in local and diversified agricultural systems. As the midwestern grape industry reemerges, it is important to encourage sustainable land management practices that are environmentally sound, economically viable, and socially responsible (Ingles 1992). This entails implementation of weed management practices that control weeds, promote grapevine productivity and fruit quality, and maintain soil quality.

Weeds compromise crop productivity through competition for resources including water, nutrients, and light. Weeds also can harbor and vector plant pests and pathogens (Wisler and Norris 2005). Unabated weeds threaten grapevine performance and productivity, particularly in organic vineyards where herbicide use is restricted (Delate and Friedrich 2004). Conventional weed management in the Midwest entails pre- and post-emergent herbicide applications and/or mechanical cultivation underneath vineyard rows, while permanent vegetative groundcovers are maintained between rows. The short-term effectiveness of these techniques has enabled growers to cultivate grapes. However, questions regarding the long-term impacts of these practices on grapevine productivity and soil quality remain unanswered.

Soil quality is defined as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and to support human health and habitation" (Karlen et al. 1997). Evaluations of soil quality emphasize consideration of chemical, physical, and biological properties of soil (USDA 1999). Conventional practices, such as maintaining bare soil through continual herbicide use and/or cultivation, lessen soil quality due to reduced organic matter and erosion. Cultivation and/or herbicide applications reduce vegetative groundcover and subsequent organic-matter input. Erosion and loss of soil structure are thereby exacerbated, while nutrient- and water-holding capacity, infiltration, and biological activity are reduced (Glover et al. 2000; Merwin et al. 1994; Smith et al. 2008). Excessive use and/or mismanagement of agrichemicals, such as herbicides, also may lead to accidental exposure to applicators and field workers, residuals and runoff, decreases in nontarget and/or beneficial-organism populations, and evolved resistance in target-organism populations (Pimentel et al. 1992).

Living mulches are vegetative groundcovers maintained as companion crops underneath or between vineyard rows. Benefits of living mulches include reductions in weed populations, soil erosion, and agrichemical runoff (Hartwig and Ammon 2002). Consequently, soil organic matter content, soil structure, soil fertility, and crop productivity are improved. Despite the potential ability of living mulches to improve soil quality, information regarding their competitive effects on grapevine growth and development is conflicting. Water stress, which may be imposed by plant competition, can impair grapevine growth and development, as well as subsequent fruit productivity and quality (Morlat and Jacquet 2003; Shellie 2006). Current research indicates plant competition imposed by living mulches has varying effects and depends on the environmental conditions of a given location. For example, Tesic et al. (2007) investigated the effects of living groundcovers of resident vegetation within hot/semiarid and mild/semihumid climates of Australia. Competition imposed by the groundcovers decreased grapevine petiole nutrient content, vegetative growth, fruit yield, and berry weight. Yet, the competitive effects were less pronounced in the mild/semihumid climate, where moisture was less limiting.

The objective of this study was to evaluate the effects of irrigation on established grapevine growth and development when grown with and without living mulches. Due to the potential competitive effects of living mulches, it is expected grapevines grown with living mulches will have reduced vegetative growth and fruit yield. Through the provision of supplemental irrigation, it is anticipated competition between grapevines and living mulches will be mitigated. A sub-objective of the study was to evaluate treatment impact on weed control and soil quality. With increased interest in sustainable approaches to vineyard weed management, research addressing the impact of living mulches on Midwest grapevine growth and development, as well as in other continental-climate locations with rain-fed agriculture, is needed before adoption. Success of the revitalized Midwest grape and wine industry largely depends on the implementation of weed control strategies that maintain grapevine growth and development, while conserving soil quality.

Materials and Methods

Vineyard site

The experiment was conducted from 2007 to 2009 in a vineyard established in 1985 at the Iowa State University Horticulture Research Station near Ames, IA (latitude 42˚06’29”N; longitude 93˚35’ 09”W). Statewide climate is continental and the growing season extends from Mar. to Oct. Temperature and precipitation data were retrieved from the Iowa Environmental Mesonet (IEM) website (http://mesonet.agron.iastate.edu/). For the 2007, 2008, and 2009 growing seasons, total precipitation was 880, 1140, and 850 mm, respectively. The average high and low air temperatures for the 2007 growing season were 23 and 12 ^{o}C, respectively. The average high was 21 ^{o}C in 2008 and 19 ^{o}C in 2009. The average low was 9 ^{o}C for both the 2008 and 2009 growing seasons. Soil was a Clarion loam on a 2 to 9% slope. Formed from superglacial till, Clarion loam is a fine-loamy, mixed, superactive, mesic Typic Hapludoll with moderately good drainage and a high available water holding capacity (USDA 1984). The vineyard site was untiled with rows in a north-south orientation. All vines were trained to a six-cane kniffen and spaced 1.8 m within the row and 2.7 m between rows. From 1985 to 2003, herbicide applications were used to control weeds within a 0.9-m-wide area underneath the vineyard row, while a 1.8-m-wide strip of Kentucky bluegrass (*Poa pratensis* L.) and resident vegetation was maintained between rows. Fertilizer and pesticide applications for disease and insect control followed extension recommendations (Dami et al. 2005; Bordelon et al. 2008).

Experimental design

The experimental design was a randomized complete block with four treatments replicated eight times. Thirty-two plots, each 7.3 × 0.9 m, were treated as experimental units. Observations were made on four grapevines and averaged for each unit. Each plot received one of the following treatments applied within a 0.9-m-wide area underneath the vineyard row: 1) herbicide application without irrigation (herbicide), 2) herbicide application with irrigation (herbicide + irrigation), 3) living mulch without irrigation (living mulch), and 4) living mulch with irrigation (living mulch + irrigation). Treatment applications were initiated in fall 2007 and continued through 2009. Herbicide applications followed recommendations prescribed by the Midwest Commercial Small Fruit and Grape Spray Guide (Bordelon et al. 2008). After weed data collection, glyphosate was applied at a rate of 1.1 kg a.i./ha. A groundcover of shade-tolerant creeping red and Chewings fescue [*Festuca rubra* L. 'Foxy' and *F. rubra* var. *fallax* (Thuill.) Hack. 'Ambrose,' respectively] was established 10 Oct. 2007 and seeded at a rate of 20.1 g/m^2. The fescue was overhead-irrigated until establishment and not over-seeded throughout the experiment. Mowing of the fescue occurred May 2009. Mowing was performed to assess establishment and recovery of the fescue after spring flooding in 2008.

Supplemental irrigation in treatment plots was provided by drip irrigation. Irrigation scheduling regimes were based on fescue evapotranspiration, whereby daily fescue evapotranspirative water loss was calculated with the modified Penman equation (Doorenbos and Pruitt 1977). Site-specific weather data, including daily precipitation and reference evapotranspiration (ETr), were collected daily through the IEM website (http://mesonet.agron.iastate.edu/). No irrigation was supplied in 2008 due to abundant spring rains and flooding. In 2009, irrigation was provided 11 times from May through Sept. (29 May, 18 June, 26 June, 1 July, 13 July, 20 July, 27 July, 3 Aug., 12 Aug., 25 Aug., and 4 Sept.). An irrigation event was triggered when accumulative evapotranspiration reached a predetermined threshold value of 6.6 cm/ha. At this threshold, 45% of the available soil water had been depleted. Depleted water was subsequently replenished to field capacity through the application of 2,813 L of irrigation water per hectare over the course of 48 hr. Water was supplied by five drip-emitters per plot. Emitters were placed between grapevines and delivered water at a rate of 3.8 L/hr. To measure soil moisture tension, tensiometers (Irrometer®, Riverside, CA, USA) were installed to depth of 15.2 and 30.5 cm within each plot during the spring of 2008 and 2009. Matric water potential (Ψ_m) was measured three times a week at 0800 hr throughout the growing season.

Grapevine sampling

The table grape cultivars, Reliance and Swenson Red (*Vitis labrusca* L.), were used in the experiment. 'Reliance' was balanced pruned with a 20 + 10 bud adjustment, while 'Swenson Red' was pruned with a 25 + 10 bud adjustment. Pruning occurred in March and April of 2008 and 2009, respectively. During pruning, weights of dormant canes were collected to measure grapevine vegetative growth. Cluster thinning was performed after berry set. ‘Reliance’ was thinned to 1 cluster per shoot and ‘Swenson Red’ was thinned to 2 clusters per shoot. In Aug. 2008 and Aug. 2009, 150 to 200 petioles were collected per plot. Petioles were analyzed for nutrient content by A & L Great Lakes Laboratory, Inc., Fort Wayne, IN.

Harvesting of ‘Reliance’ grapes occurred on 18 Aug. 2008 and 21 Aug. 2009. ‘Swenson Red’ grapevines were harvested on 19 Sept. 2008 and 15 Sept. 2009. At harvest, yield data, including per-grapevine weight, cluster number, and average cluster weight were determined. Samples of 50 berries were collected randomly from grapevine clusters within each experimental plot and frozen for subsequent fruit quality analyses. Mean berry weight, percentage soluble solids [SSC(%)/Brix], initial pH, and titratable acidity were determined after thawing (Amerine and Ough 1980).

Weed sampling

Weed control was measured during 2008 and 2009 in May, June, July, and Aug. via visual estimates of percentage weed cover and total monocot and dicot shoot biomass. Visual estimates were collected from three randomly placed 0.25 m^2 quadrats per plot. All weeds within each quadrat were harvested, separated as a monocot or dicot, and processed. Processing entailed root removal and drying of shoots at 67 ºC for 72 h before biomass was determined.

Soil sampling

Soil samples from ‘Reliance’ plots were collected on 29 Sept. 2007, 31 Oct. 2008, and 4 Nov. 2009. ‘Swenson Red’ soils were collected on 28 Sept. 2007, 2 Nov. 2008, and 3

Nov. 2009. Composite samples representative of each experimental unit were collected from 12 randomized soil cores that were 15.2 × 3.1 cm. Cores were divided into subsamples at 0- to 7.6-cm and 7.6- to 15.2-cm depths. Within 24 h after collection, soils were passed through an 8-mm sieve and allowed to air-dry at 22 ± 1 ºC before being stored in a 3 ± 1 ºC cooler for subsequent analyses.

Soil-quality analyses entailed measurements of chemical, physical, and biological soil properties. Chemical properties measured were pH, percentage organic matter, total organic carbon (C) and nitrogen (N), inorganic mineral nitrogen (NH_3-N and NO_3-N), Bray-1 phosphorus (P), and cations of potassium (K), magnesium (Mg), and calcium (Ca). Soil pH was measured with a HANNA H19813 meter (HANNA Instruments®, Woonsocket, RI, USA) by using a 1:1 dilution of deionized water and soil (USDA 1999). Percentage organic matter and total C and N were determined by combustion analysis (Combs and Nathan, 1998) in an elemental analyzer (Haake Buchler Instruments, Paterson, NJ, USA). Inorganic mineral N was determined colorimetricallly by the cadmium reduction method (Gelderman and Beegle 1998). Phosphorus was extracted according to the procedure outlined by Frank et al. (1998). Potassium, Mg, and Ca were assayed using a Mehlich-3 extraction (Warncke and Brown 1998).

Measured physical soil properties included bulk density, total porosity, water-filled pore space, gravimetric and volumetric water content, flooded/ponded initial infiltration rate, and stable aggregate content. Gravimetric water content was determined immediately after fall soil collection by oven-drying field-moist soil for 24 h at 105 ºC (USDA 1999). Bulk density and infiltration measurements were collected only in 2009 due to excessively wet soil conditions in previous years. Soils from measures of bulk density were used to calculate volumetric soil water content by drying 60 cm^3 of field-moist soil for 24 h at 105 ºC (USDA 1999). Total and water-filled pore spaces were calculated from measures of bulk density and water content. Infiltration rate was measured according to the USDA (1999). Stable aggregate content was measured according to the procedure described by Patton et al. (2001).

Potential soil enzymatic activity was quantified via fluorescein diacetate (FDA) hydrolysis (Green et al. 2006). Esterases, lipases, and proteases produced by soil organisms hydrolyze FDA-containing substrates and produce fluorescein. Fluorescein was quantified with a Spectronic 20D+ spectrophtometer (Spectronic Analytical Instruments, Leeds, UK) at 490 nm.

Data analysis

All data were analyzed with Statistical Analysis System software using a mixed model (PROC MIXED) procedure and a least-squares mean (lsmeans) option (version 9.1; SAS Institute, Cary, NC). For tests of significance ($P \leq 0.05$), means were separated with a Tukey-Kramer adjustment for multiple comparisons. Excluding measures of grapevine performance and fruit quality, data from ‘Reliance’ and ‘Swenson Red’ were combined. Due to flooding in 2008, no irrigation treatments were applied. Consequently, only 2009 data are presented.

Results

Grapevine growth and yield

Few differences in grapevine growth and yield were observed. The only observed difference occurred with ‘Reliance’ grapevines, which had increased pruning weights in the herbicide + irrigation treated plots (Table 1) in early spring 2009 from vines that did not receive irrigation application in 2008. Nutrient content of 'Reliance' and 'Swenson Red' petioles were the same across all treatments (Appendix Tables 8 and 9).

Fruit quality

'Reliance' berry weight and pH were greatest in herbicide + irrigation treated plots, while Brix and titratable acidity were similar across all treatments (Table 2). 'Swenson Red' berry weight and Brix were greater in living mulch + irrigation treated plots. Fruit pH was greatest in living mulch plots, while titratable acidity was the same across all treatments.

Weed cover and biomass

Overall percentage weed cover and weed shoot biomass were lower in both living mulch plots (Fig. 1, Table 3). In May, percentage weed cover was similar in herbicide + irrigation plots and both living mulch plots, whereas it was greatest in herbicide-treated plots (Fig. 1). Percentage weed cover was greatest in both herbicide-treated plots in July. Aug. percentage weed cover was the same across all treatments. Dicot weed shoot biomass was generally greater across all treatments, particularly in herbicide-treated plots (Table 3).

Soil quality

Few differences were found in chemical and biological indicators of soil quality (Appendix Tables 10 to 17). Excluding nitrogen, chemical soil properties were the same. Only organic nitrogen and NO_3-N collected at the 0- to 7.6-cm depth in plots of 'Swenson Red' were different. Organic nitrogen and NO_3-N were greatest in herbicide + irrigation and both living mulch plots. FDA hydrolytic activity was the same across all treatments, although activity was greater at the 0- to 7.6 cm depth when compared to the 7.6- to 15.2-cm depth.

No differences in matric water potential were found (Appendix Tables 18 to 21). Despite this, water-filled pore space, water content, and volumetric water content were greater in both living mulch plots (Table 4). Aggregate stability (Appendix Tables 22 and 23), bulk density, and porosity were the same across all treatments. Infiltration was slowest in both herbicide-treated plots, whereas it was fastest in living mulch plots.

Discussion

To our knowledge, this research is the first to evaluate the effects of vineyard weed management and irrigation practices on grapevine performance within the unique climatic and soil conditions experienced in the Midwest. Living mulches and irrigation had no consistent effect on grapevine growth and development, suggesting little-to-no competition existed between the grapevines and living mulches during the period in which the study was conducted. When compared to both herbicide-treated plots, living mulches controlled weeds and promoted several indicators of soil quality.

The effects of weed management and irrigation practices on grapevine growth and development were minimal. Yield of ‘Reliance’ and ‘Swenson Red’ grapevines were unaffected by the imposed treatments (Table 1). Only pruning weights of ‘Reliance’ grapevines receiving the herbicide + irrigation treatment were greater. Considering all other measures of yield and growth were the same, it remains questionable as to if the observed increase in pruning weights was a treatment effect. The observed increase may have been due to individual grapevine variability previously present within the field. Moreover, spring flooding in 2008 could have altered grapevine growth and development in the subsequent growing season, thereby masking possible treatment effects. Nevertheless, given that no other differences in grapevine yield were detected, our data shows living mulches and irrigation had no effect on yield during the period in which the study was conducted.

Measured fruit quality variables were all within acceptable ranges. ‘Reliance’ berry weight was greatest in herbicide + irrigation plots, which also had greater pruning weights (Tables 1 and 2). For ‘Swenson Red,’ berry weight was greatest in the living mulch + irrigation plots (Table 2). Because consistent effects on berry size were not observed, our findings show berry size was not affected by living mulches nor irrigation. Based on previous reports of competition resulting in smaller berry sizes, we conclude competition was not a factor in our observed differences in berry size (Monteiro and Lopes 2007; Tesic et al. 2007). Similarly to yield and growth data, observed differences may be due to individual grapevine variability. Contrary to expectations, Brix was also greater in ‘Swenson Red’ fruit harvested from living mulch + irrigation plots. Popular belief assumes increased berry size is due to increased water within fruit, which dilutes sugars and decreases Brix. Yet, our results show otherwise. Reynolds et al. (2007) found similar results in an Ontario vineyard. Under varying irrigation regimes, fruit from irrigated treatments had overall higher yields and Brix when compared to fruit from nonirrigated and early irrigation cut-off treatments. These results suggest berry size may not be an accurate indicator of Brix.

Percentage weed cover and weed shoot biomass were lower in both living mulch plots (Fig. 1, Table 3). These findings are consistent with previous research (Hartwig and Ammon 2002; Ingels et al. 2005). By maintaining a permanent groundcover, weed-seed germination and growth are inhibited, consequently reducing weed populations. In contrast, exposed soil provides a favorable environment for seed germination and growth, as reflected by the overall greater percentage weed cover and biomass observed in both herbicide-treated plots.

All physical soil quality indicators were within USDA-recommended ranges (USDA 1999). Even though no differences in matric water potential were detected, water-filled pore space, water content, and volumetric water content were greater in both living mulch plots (Table 4). The lack of differences in matric water potential relative to the other measures of soil water content may be due to the accuracy of our tensiometers. Challenges with the tensiometers were routinely experienced, which resulted in their continual reinstallation. Due to this, analysis and interpretation of tensiometer data should be approached with caution. For future studies, we advise using other tools for more accurate measures of matric water potential.

Living mulches enhanced soil quality, namely the physical soil quality indicator of infiltration (Table 4). Mulches increase soil organic matter content, which stabilizes soil aggregates and reduces their breakdown, decreases surface crusting, and enhances infiltration (Sikora and Stott 1996). Surface crusting (visual observation) and slower infiltration rates were noted in herbicide-treated plots, demonstrating the beneficial effects mulches have on physical soil properties. While few differences in chemical soil properties were observed, continued monitoring is recommended because conventional testing procedures may not detect differences for several years (Sikora and Stott 1996). Likewise, continued monitoring of biological indicators of soil quality is recommended. Because soil biological activity is largely dependent on carbon-source availability, the lack of differences in soil chemistry (especially carbon) may explain why differences in biological activity were not observed

(Dick et al. 1996). Furthermore, the methodology of measuring potential enzymatic activity may not be robust enough and in need of optimization

Conclusion

This study provides information on weed management and irrigation practices for the unique and rapidly expanding grape and wine industry of the Midwest. Despite concerns of competition, this study demonstrates that living mulches maintain grapevine growth and development, control weed populations, and enhance soil quality. Moreover, irrigation had no consistent effect on grapevine growth and development during the period in which the study was conducted. Abnormally wet conditions could have mitigated competition between the grapevines and living mulch, thereby explaining the lack of differences in grapevine performance. Under normal climatic conditions of the Midwest, reduced moisture could jeopardize grapevine performance due to water competition between grapevines and living mulch. Continued monitoring and evaluation will provide additional insight regarding the practicality of living mulches within midwestern vineyards. To date, our study indicates competition imposed by living mulches is minimal and that living mulches are a viable option for weed management that contribute to aspects of sustainability.

Literature Cited

Amerine, M.A. and C.S. Ough. 1980. Methods for Analysis of Musts and Wines. John Wiley and Sons. New York, NY.

Bordelon, B., M. Ellis, and R. Weinzierl (eds.). 2008. Midwest Commercial Small Fruit and Grape Spray Guide 2008. Purdue Univ., West Lafayette, Ind.

Combs, S.M. and M.V. Nathan. 1998. Soil Organic Matter. *In* Recommended Chemical Soil Test Procedures for the North Central Region. J.R. Brown (ed.), pp. 53-58. North Central Regional Research Publication No. 221. Missouri Agricultural Experiment Station. Columbia, MO.

Dami, I., B. Bordelon, D.C. Ferree, M. Brown, M.A. Ellis, R.N. Williams, and D. Doohan. 2005. Midwest grape production guide. Ohio State Univ. Ext. Bul. 919-05.

Delate, K. and H. Friedrich. 2004. Organic apple and grape performance in the midwestern U.S. Acta Hort. 638:309-320.

Dick, R.P., D.P. Breakwell, and R.F. Turco. 1996. Soil enzyme activities and biodiversity measurements as integrative microbiological indicators. *In* Methods for Assessing Soil Quality. J.W. Doran and A.J. Jones (eds.), pp. 247-271. SSSA Special Publication 49. Soil Sci. Soc. Amer., Madison, WI.

Doorenbos, J. and W.O. Pruitt. 1977. Guidelines for predicting crop water requirements. FAO Irrig. Drain. Paper No. 24. 2nd ed. Food Agr. Org. United Nations, Rome, Italy.

Frank, K., D. Beegle, J. Denning. 1998. Phosphorus. *In* Recommended Chemical Soil Test Procedures for the North Central Region. J.R. Brown (ed.), pp. 21-29. North Central Regional Research Publication No. 221. Missouri Agricultural Experiment Station. Columbia, MO.

Gelderman, R.H. and D. Beegle 1998. Nitrate-Nitrogen. *In* Recommended Chemical Soil Test Procedures for the North Central Region. J.R. Brown (ed.), pp. 17-20. North Central Regional Research Publication No. 221. Missouri Agricultural Experiment Station. Columbia, MO.

Glover, J.D., J.P. Reganold, and R.K. Andrews. 2000. Systematic method for rating soil quality of conventional, organic, and integrated apple orchards in Washington state. Agricult. Ecosys. Environ. 80:29-45.

Green, V.S., D.E. Scott, and M. Diack. 2006. Assay for fluorescein diacetate hydrolytic activity: Optimization for soil samples. Soil Biol. Biochem. 38:693-701.

Hartwig, N.L. and H.U. Ammon. 2002. Cover crops and living mulches. Weed Sci. 50:688-699.

Ingles, C.A. 1992. Sustainable agriculture and grape production. Am. J. Enol. Vitic. 43:296-298.

Karlen, D.L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Sci. Soc. Amer. J. 61:4-10.

Merwin, I.A., W.C. Stiles, and H.M. Van Es. 1994. Orchard groundcover management, impacts on soil physical properties. J. Am. Soc. Hort. Sci. 119:216-222.

Monteiro, A. and C.M. Lopes. 2007. Influence of cover crop on water use and performance of vineyard in Mediterranean Portugal. Agric. Ecosyst. Environ. 121:336-342.

Morlat, R. and A. Jacquet. 2003. Grapevine root system and soil characteristics in a vineyard maintained long-term with or without inward sward. Am. J. Enol. Vitic. 54:1-7.

Patton, J.J., L. Burras, M.E. Konen, and N.E. Molstad. 2001. An accurate and inexpensive apparatus and method for teaching and measuring stable aggregate content of soils. J. Nat. Resour. Life Sci. Educ. 30:84-88.

Pimentel, D., H. Acquay, M. Biltonen, P. Rice, M. Silva, J. Nelson, V. Lipner, S. Giordano, A. Horowitz, and M. D'Amore. 1992. Environmental and economic costs of pesticide use. BioScience 42:750-760.

Reynolds, A.G., W.D. Lowrey, L. Tomek, J. Hakimi, and C. de Savigny. 2007. Influence of irrigation on vine performance, fruit composition, and wine quality of Chardonnay in a cool, humid climate. Am. J. Enol. Vitic. 58:217-228.

Shellie, K.C. 2006. Vine and berry response of Merlot (*Vitis vinifera* L.) to differential water stress. Am. J. Enol. Vitic. 57:514-518.

Sikora, L.J. and D.E. Stott. 1996. Soil organic carbon and nitrogen. *In* Methods for Assessing Soil Quality. J.W. Doran and A.J. Jones (eds.), pp. 157-167. SSSA Special Publication 49. Soil Sci. Soc. Amer., Madison, WI.

Smith, R., L. Bettiga, M. Cahn, K. Baumgartner, L.E. Jackson, and T. Bensen. 2008. Vineyard floor management affects soil, plant nutrition, and grapevine yield and soil quality. Calif. Agric. 62:184-190.

Tesic, D., M. Keller, and R.J. Hutton. 2007. Influence of vineyard floor management practices on grapevine growth, yield, and fruit composition. Am. J. Enol. Vitic. 58:1-11.

United States Department of Agriculture (USDA). 1984. Soil Survey of Story County, Iowa. Soil Conservation Service.

United States Department of Agriculture (USDA). 1999. Soil quality test kit guide. U.S. Dept. Agric., Agric. Res. Serv., and Nat. Resources Cons. Serv.

Warncke, D. and J.R. Brown. 1998. Potassium and other basic cations. *In* Recommended Chemical Soil Test Procedures for the North Central Region. J.R. Brown (ed.), pp.

31-34. North Central Regional Research Publication No. 221. Missouri Agricultural Experiment Station. Columbia, MO.

White, M.L. and M.R. Dharmadhikari. 2008. The Iowa boom includes wine. Wine east: News of grapes and wine in eastern North America. 36:12-55.

Wisler, G.C. and R.F. Norris. 2005. Interactions between weeds and cultivated plants as related to management of plant pathogens. Sym. Weed Sci. 53:914-917.

Table 1. Yield and growth of ‘Reliance’ and ‘Swenson Red’ grapevines grown under four weed management and irrigation treatments in 2009. Treatments were replicated four times in 16 plots for each cultivar. Observations were made on four grapevines per plot and averaged for each experimental unit.

	‘Reliance’				‘Swenson Red’			
Treatment	Yield (kg/vine)	Vine cluster no.	Avg cluster wt (g)	Pruning wt (kg/vine)	Yield (kg/vine)	Vine cluster no.	Avg cluster wt (g)	Pruning wt (kg/vine)
Herbicide	2.8 a[a]	14 a	184.3 a	0.91 ab	4.4 a	65 a	59.1 a	0.74 a
Herbicide + irrigation	3.2 a	15 a	207.8 a	1.49 a	5.8 a	69 a	80.0 a	0.65 a
Living mulch	3.1 a	16 a	203.5 a	1.1 ab	5.1 a	55 a	86.9 a	0.54 a
Living mulch + irrigation	2.5 a	13 a	190.3 a	1.02 ab	6.0 a	63 a	112.3 a	0.47 a

[a]Means of four replications calculated from four grapevines per experimental unit, or plot, with 16 units total; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Table 2. Fruit quality of ‘Reliance’ and ‘Swenson Red’ grapevines grown under four weed management and irrigation treatments in 2009. Treatments were replicated four times in 16 plots for each cultivar. Observations were made on four grapevines per plot and averaged for each experimental unit.

	‘Reliance’				‘Swenson Red’			
Treatment	Berry wt (g)[a]	Brix[b]	pH	Titratable acidity (g/L)	Berry wt (g)	Brix	pH	Titratable acidity (g/L)
Herbicide	2.76 a[c]	17.8 a	3.10 a	0.90 a	3.25 a	18.7 a	3.38 a	0.52 a
Herbicide + irrigation	3.04 b	17.9 a	3.11 ab	0.93 a	3.29 a	19.1 a	3.38 a	0.49 a
Living mulch	2.70 a	17.7 a	3.07 a	0.97 ab	3.26 a	18.7 a	3.33 b	0.50 a
Living mulch + irrigation	2.65 a	17.9 a	3.08 a	0.93 a	3.46 ab	19.6 b	3.40 a	0.47 a

[a]Fruit quality variables calculated from a 50-berry sample.
[b]Percentage soluble solids concentration (%SSC).
[c]Means of four replications calculated from four grapevines per experimental unit, or plot, with 16 units total; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Table 3. Shoot biomass of monocot and dicot weeds collected from rows of ‘Reliance’ and ‘Swenson Red’ that received one of four weed management and irrigation treatments in 2009. Treatments were replicated four times in 16 plots for each cultivar and combined. Percentage weed cover was calculated from averages of three 0.25-m^2 quadrats per plot.

	Weed shoot biomass (g)					
	May		July		Aug.	
Treatment	Monocot	Dicot	Monocot	Dicot	Monocot	Dicot
Herbicide	1.3 a[a]	4.9 b	0.3 a	16.6 b	0 a	2.3 b
Herbicide + irrigation	1.9 a	3.4 ab	0.5 a	4.5 a	1.0 a	1.7 ab
Living mulch	1.5 a	1.8 a	0.2 a	0.6 a	0.2 a	0.2 a
Living mulch + irrigation	2.1 a	1.6 a	0.2 a	0.6 a	0.5 a	0.2 a

[a]Values are means of 32 experimental units with four replications; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Table 4. Indicators of soil quality from vineyard soils receiving four weed management and irrigation treatments in 2009. Treatments were replicated four times in 32 plots. Measurements of physical soil quality indicators were collected from three samples per plot and averaged for each experimental unit.

Treatment	Bulk density (g/cm)	Porosity (%)	Water-filled pore space (%)	Water content (%)	Volumetric water content (%)	Initial infiltration[a] (min)
Herbicide	1.31 a[b]	50 a	46 a	17 a	23 a	17.7 c
Herbicide + irrigation	1.28 a	48 a	47 ab	18 a	22 a	16.2 c
Living mulch	1.23 a	46 a	56 b	21 b	26 b	3.4 a
Living mulch + irrigation	1.24 a	47 a	60 b	23 b	27 b	7.8 b

[a]Time for 2.5 cm of water to infiltrate into soil.
[b]Means from four replications of 32 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment .

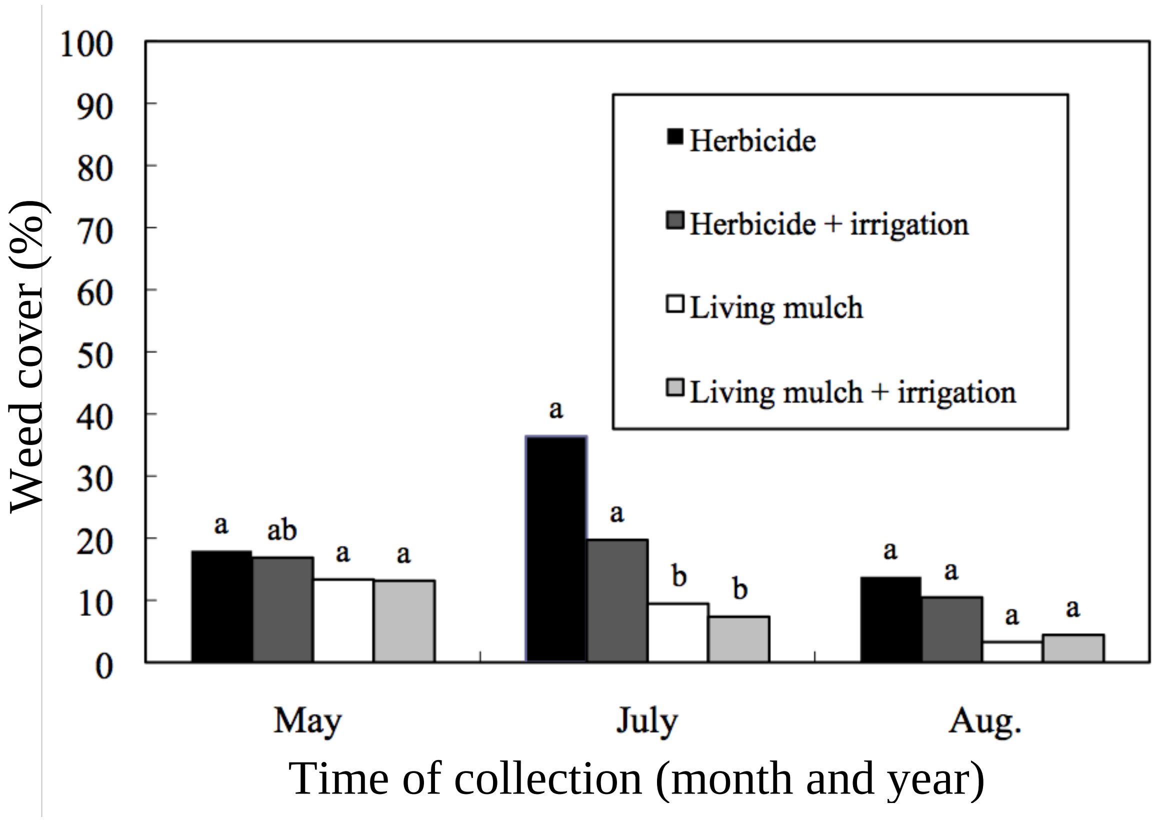

Fig. 1. Percentage weed cover estimated visually from rows of 'Reliance' and 'Swenson Red' receiving four weed management and irrigation treatments in 2009. Treatments were replicated four times in 16 plots for each cultivar and combined. Percentage weed cover was calculated from averages of three 0.2-m^2 quadrats per plot. Percentages with the same letter are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

CHAPTER 4. SURVEY OF IOWA FRUIT GROWERS' AWARENESS OF WEED MANAGEMENT AND SOIL QUALITY

A paper to be submitted to the *HortTechnology*

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Additional index words. sustainable horticulture, grower survey, soil management, extension education, alternative weed management

Abstract. The long-term productivity and sustainability of a horticultural enterprise depends on the implementation of land management practices that maintain and/or enhance soil quality. Weed management is one practice that can profoundly impact soil quality. As land managers and decision makers, fruit growers are of critical importance in the maintenance of soil quality by how they approach weed control. Grower awareness of practices that maintain, diminish, or enhance soil quality is important in the promotion of sustainable crop production. The objective of this study was to survey Iowa fruit growers' awareness of alternative weed management practices that maintain or enhance soil quality. Twenty-two participants were surveyed at a field day and conference. All survey participants were aware of soil quality and considered the quality of their soils when making land management decisions. Most were aware of alternative weed management practices, yet some were uncertain about the outcome of implementing alternative practices within their own production systems. To advance the awareness and adoption of alternative weed management and soil-quality concepts, future extension programs should focus on educating growers how weed management decisions can impact both crop productivity and soil quality.

The long-term productivity and sustainability of a horticultural enterprise depends on soil quality. Conventional weed management practices, such as maintaining bare soil through repeated application of herbicides and/or tillage (also known as “cultivation”), accelerate losses of soil quality. Some claim the ubiquitous use of synthetic agrichemicals, including herbicides, is the greatest threat to sustainable fruit production (Merwin and Pritts, 1993). Without protective groundcovers, bare soil surfaces are susceptible to physical forces that favor degradation. For example, raindrop impact can dislodge exposed soil particles, thereby favoring erosion. Such losses of soil quality can have negative on- and off-site consequences, including declines in crop productivity and pollution of surface waters (Lal et al., 2004).

Bare soil also limits additions of organic matter. Organic matter is often considered a key indicator of soil quality due to its diverse roles in chemical, physical, and biological soil processes (Sikora and Stott, 1996). Reductions in soil organic matter and concomitant declines in soil quality have been observed within production systems managed with herbicides and/or tillage. Merwin et al. (1994) found herbicide application and tillage in orchard production systems reduced soil organic matter levels, while declines in physical attributes of soil quality were accelerated. Similar findings were reported by Glover et al. (2000), who found continual use of herbicides in orchards reduced soil aggregate stability, microbial biomass, and earthworm counts, while bulk density (compaction) increased. Many of these properties are essential in maintaining the tilth, fertility, and long-term productivity of a horticultural enterprise.

Farmer-based surveys about soil quality have been conducted among Midwest grain and dairy farmers during the development of soil heath scorecards (Romig et al., 1996).

However, information about Midwest fruit growers' knowledge and awareness of soil quality is lacking. With the reemergence of the Iowa grape industry, as well as increased interest in diversified food production systems, it is important to gauge fruit growers' knowledge and awareness of soil quality. To sustainably manage soils and ensure long-term productivity, growers need to be aware of practices that optimize soil quality. Alternative weed management practices, such as mulches, have the potential to mitigate declines in, or enhance, soil quality (Hartwig and Ammon, 2002). Mulches provide a protective barrier from degradative forces and can supply organic matter to soils, thereby promoting soil quality.

The objective of this study was to survey Iowa fruit growers' awareness of alternative weed management practices that maintain or enhance soil quality. With survey information, responses can be analyzed and utilized in developing future extension-education programs. Such programs that inform and empower growers to manage their lands in ways that optimize soil quality will be critical in the promotion of sustainable land management for the Midwest's reemerging fruit industry.

Materials and Methods

Sample population and instrumentation. Fruit growers attending the Iowa State University (ISU) All-Horticulture Field Day and Iowa Fruit and Vegetable Growers Association (IFVGA) annual conference were surveyed. Prior to survey implementation, institutional approval was obtained. Field day surveys were conducted on 6 Aug. 2009, while conference surveys were conducted 29 and 30 Jan. 2010. Subjects were requested to anonymously complete a brief survey consisting of nine questions. After consenting, subjects independently completed and returned the survey to the investigators.

Data analysis. A total of 22 surveys were completed between the two venues. Survey results from each venue were combined. Descriptive statistics consisting of mean percentages were calculated for each question on the survey. Results to each question are reported in Table 1 of the results and discussion section.

Results and Discussion

All survey participants were aware of soil quality and considered the quality of their soils when making land management decisions (Table 1). Eighty-six percent of respondents believed soil quality was important for the production of their crops, while five percent believed soil quality was unimportant. The remaining nine percent indicated they did not know if soil quality was important for the production of their crops, implying a lack of knowledge or level of uncertainty regarding the importance of soils in crop production. Thirteen percent of growers believed poor soil quality did not reduce yield and/or the quality of their crops, while 82% believed poor soils did reduce crop yield and/or quality. Of the 13% that believed poor soil quality had not contributed to yield and/or quality losses, pests and poor weather were often held accountable as the predominant factor causing yield and/or quality declines (personal communication with survey participants).

Conventional methods of weed control were described as herbicide application and/or cultivation. Half of the respondents reported using conventional methods of weed control, while 45% claimed they did not. Respondents that did not used conventional methods of weed control reported to use “organic methods,” such as mulching or the use of organicapproved herbicides. The five percent of respondents that did not know if they were using "conventional herbicides" stated that they either experienced difficulty understanding to the term "conventional herbicides" in the survey, or used a mixture of conventional and alternative approaches to weed management. The majority of respondents were aware of alternatives to conventional herbicides. Seventy-seven percent of respondents were aware of weed management alternatives that promote soil quality. The remaining 23% were unaware, or did not know of, alternative weed management practices that promote soil quality. This lack of knowledge and level of uncertainty suggests growers are aware of alternatives to conventional weed management, yet do not know how certain alternative practices can impact soil quality.

The percentage of uncertainty (participants responding "don't know") increased to 23% when asked about their interest in alternatives to herbicides that promote soil quality within their own production systems. These participants stated that they needed more information about the costs and benefits of a particular practice prior to implementation. Socioeconomic factors may explain the increased level of uncertainty. Despite the reputed long-term benefits of soil-conserving alternative practices, growers may be reticent to abandon conventional practices that promise short-term profitability (Merwin and Pritts, 1993). Nevertheless, the majority of participants stated that they did not think practices promoting soil quality would compromise crop productivity. Eighteen percent of participants reported they did not know if soil-quality promoting practices would compromise crop yield. These uncertain participants recognized the complexity of crop response and how it can vary within a given horticultural and environmental setting. Recognizing this, these participants stated that more information was needed for them to respond with certitude.

Overall, growers were cautious about the adoption and implementation of alternative weed management practices. This caution is warranted given that growers' livelihoods are contingent upon successful crop production. To advance the awareness and adoption of alternative weed management and soil-quality concepts, future extension programs should emphasize and demonstrate how weed management practices can impact crop productivity and soil quality. Knowledge networks comprised of growers, farm advisors, researchers, and extensionists are also a promising approach in the development of sustainable land management (Jorden et al., 2003). Such networks differ from normal extension programs in that a group of professionals with diverse skills routinely meet to collectively share information that unites them in solving a shared agricultural/horticultural issue. Through this sharing and integration of knowledge, growers would be able to learn about viable weed management practices that are a component to sustainable land management that promote soil quality.

Literature Cited

Glover, J.D., J.P. Reganold, and R.K. Andrews. 2000. Systematic method for rating soil quality of conventional, organic, and integrated apple orchards in Washington state. Agricult. Ecosys. Environ. 80:29-45.

Hartwig, N.L. and H.U. Ammon. 2002. Cover crops and living mulches. Weed Sci. 50(6):688-699.

Jordan, N., R. Becker, J. Gunsolus, and S. Damme. 2003. Knowledge networks: an avenue to ecological management of invasive weeds. Weed Sci. 51:271-277.

Lal, R., T.M. Sobecki, T. Iivari, and J.M. Kimble. 2004. Water and wind erosion on U.S. cropland, pp. 109-130. In: Soil degradation in the United States: extent, severity, and trends. Lewis Publishers, Boca Raton, FL.

Merwin, I.A. and M.P. Pritts. 1993. Are modern fruit production systems sustainable? HortTechnology. 3(2):128-136.

Merwin, I.A., W.C. Stiles, and H.M. Van Es. 1994. Orchard groundcover management , impacts on soil physical properties. J. Amer. Soc. Hort. Sci. 119(2):216-222.

Romig, D.E., M.J. Garlynd, and R.F. Harris. 1996. Farmer-based assessment of soil quality: a soil health scorecard, pp. 39-60. In: Methods for Assessing Soil Quality. J.W. Doran and A.J. Jones (eds.). SSSA Special Publication 49. Soil Sci. Soc. Amer., Madison, WI.

Sikora, L.J. and D.E. Stott. 1996. Soil organic carbon and nitrogen, pp. 157-167. In: Methods for Assessing Soil Quality. J.W. Doran and A.J. Jones (eds.). SSSA Special Publication 49. Soil Sci. Soc. Amer., Madison, WI.

Table 1. Alternative weed management and soil quality survey responses from 22 Midwest fruit growers. Surveys were conducted on 6 Aug. 2009 at the ISU All-Horticulture Field Day and on 29 through 30 Jan. 2010 at the IFVGA conference.

Question	Yes	No	Don't know
1. Do you consider the quality of your soil when making land management decisions (tillage, herbicides, etc.)?	100[z]	0	0
2. Are you concerned about soil quality within your own production system?	100	0	0
3. Do you believe good soil quality soil is important for the production of your crops?	86	5	9
4. Do you think poor soils have ever contributed to reduced yields and/or quality of your crops?	82	13	5
5. Do you use conventional herbicides in the production of your fruit crops?	50	45	5
6. Are you aware of alternatives to conventional herbicides for weed control?	86	9	5
7. Are you aware of alternatives to conventional herbicides that promote soil quality?	77	9	14
8. Would you be interested in herbicide alternatives that promote soil quality within your own production system?	77	0	23
9. Do you think practices that promote soil quality would compromise your own crops' productivity?	14	68	18

[z]Percentage of respondents, n = 22.

CHAPTER 5. GENERAL CONCLUSIONS

Conventional methods of vineyard weed management can promote losses of soil quality. Such losses result from weed management practices that leave soil surfaces bare, thereby exposed to degradative forces, and reduced organic matter input. With soil largely being a non-renewable resource, the continuous reduction of soil quality jeopardizes the ultimate sustainability of crop production, including vineyard production. As the grape and wine industry reemerges in the Midwest, as well as in other continental-climate locations with rain-fed agriculture, there is a need for research and development of viable weed management practices that optimize grape production and conserve soil quality.

This study addressed the aforementioned need by investigating the influence of alternative weed management practices on weed control, grapevine performance, and soil quality in an established Iowan vineyard. Specific sub-objectives addressed within individual experiments included: 1) comparing conventional and alternative weed management practices on weed control, grapevine performance, and soil quality, and 2) evaluating the influence of irrigation on grapevine growth and development, grown with and without a living mulch, on mitigation of water competition. An additional feature of this investigation was the surveying of Midwest fruit growers' attitudes and awareness of weed management practices that conserve soil resources.

Weed management

Within both experiments, straw and living mulches of fescue provided the most effective weed control when compared to cultivation and herbicide application. By maintaining a permanent groundcover, weed seed germination and growth are inhibited, consequently reducing weed populations. In contrast, exposed soil provides a favorable environment for seed germination and growth, as reflected by the overall greater percentage weed cover and biomass observed in cultivated and herbicide-treated plots. Based on these findings, we conclude mulches of straw and fescue are effective methods of weed control for Iowa vineyards.

Grapevine performance

Grapevine performance was assayed by measuring pruning weights, total fruit yield, and fruit quality of ‘Maréchal Foch’, ‘Reliance’, and ‘Swenson Red’ grapevines. Within the first experiment, ‘Maréchal Foch’ grapevine yield was unaffected by weed management treatment. However, dormant cane pruning weights were lower in cultivated plots. This observed reduction might be due to root destruction from cultivation, which can manifest into reduced shoot growth and subsequent pruning weights. All measures of fruit quality were within acceptable ranges. Fruit harvested from straw mulch plots were of slightly less quality due to reduced percentage soluble solids, increased pH, and low titratable acidity. By providing a barrier between the soil and atmosphere, the straw mulch could have caused excessive soil moisture due to reduced soil evaporation. Excessive soil moisture during critical periods of fruit development and maturation may be responsible for the observed differences in quality for fruit harvested from straw mulch plots.

In the second experiment, living mulches and supplemental irrigation had no consistent effect on ‘Reliance’ and ‘Swenson Red’ grapevine performance. When the findings from these two experiments are combined, results suggests little-to-no competition existed between the grapevines and living mulches during the period in which the study was conducted. Therefore, current findings support the conclusion that living mulches of fescue maintain grapevine performance. Nevertheless, additional research about mulches, with or without irrigation, is warranted because treatment effects may take several years to become evident and can be confounded by yearly climatic variability.

Soil quality

Alternative weed management practices of mulching promoted several indicators of soil quality. In the first experiment, no differences in chemical soil quality attributes were observed. Few differences in chemical attributes of soil quality were also observed in the second experiment. Only nitrogen was different in plots of ‘Swenson Red’, which had overall lower organic nitrogen and NO_3-N in herbicide-treated plots. Despite these lack of differences, continued evaluation of chemical properties is advised because conventional testing procedures may not be capable of detecting differences for several years.

Within both experiments, physical properties of soil quality, including water-filled pore space, gravimetric and volumetric water content, and initial infiltration rates, were greater in mulched plots. The mulch barrier between the soil and ambient environment likely reduced soil evaporation, resulting in an overall increase of soil water content during the fall in which data were collected. Organic matter is also known to stabilize soil particles, promote good structure, and facilitate rapid infiltration of water. Rapid infiltration of water prevents soil degradation by reducing surface erosion. Organic matter additions from both mulch treatments are likely responsible for the rapid initial infiltration rates observed in both experiments. Surface crusting, which is characteristic of reduced organic matter input and poor soil structure, likely favored the slower initial infiltration rates found in cultivated and herbicide-treated plots. Moreover, biopores created from increased earthworm activity, specifically in straw mulch plots, could have favored rapid infiltration.

Despite the increased population of earthworms in straw mulch plots observed within the first experiment, potential enzymatic activity of soil biota was the same across all treatments. Differences in potential enzymatic activity also were not observed in the second experiment. With soil biological activity largely dependent on carbon-source availability, the lack of differences in soil chemistry (especially carbon) may explain why differences in potential enzymatic activity were not observed. Another possibility is that native biological activity is naturally high and remained unaffected by the imposed treatments. Also, the methodology used to determine enzymatic activity may not be robust enough to detect differences. Should this be the case, the methodology for measuring potential enzymatic activity should be optimized. Data from the two experiments support the conclusion that mulches of straw and fescue promote soil quality, particularly physical attributes of soil quality, including initial water infiltration. Continued testing and monitoring of soil quality are encouraged to assess the long-term impact of weed management practices on soils.

Survey of fruit growers

The awareness, knowledge, and receptiveness of growers to alternative weed management practices are important in the development of sustainable fruit production. In a survey of Iowa fruit growers, all participants indicated they were aware of soil quality and considered the quality of soils when managing their land. Most were also aware of alternative weed management practices. Yet, several responded they were unaware of the importance soil quality has on the production of their crops and how alternative weed management practices can improve soil quality.

Growers were interested in alternative weed management practices that promote soil quality, but were cautious about implementation due to unknown costs and benefits. Such caution is expected and understandable due to the reliance growers have on crop production for their livelihoods. Findings from the survey reflect a need to continue educating growers on how land management practices, including weed control, can affect the quality of their soils and crop production. Future extension and education programs should emphasize the impact weed management practices have on soil quality and crop production in order to advance the awareness of soil quality and sustainable land management.

Future research

Due to the perennial nature of grapevines, measurable responses to various land management practices may take several years to become evident. Consequently, continued monitoring and evaluation of living mulches, as well as other alternative weed management practices, are advised before recommendation. The effects of climatic variability on grapevine growth and development, grown with and without living mulches, should also be delineated. With high-fertile soils commonly found in Iowa and other continental-climate locations with rain-fed agriculture, excessive grapevine growth can be problematic. Therefore, species of competitive living mulches that have the potential to devigorate and control overly vigorous grapevine growth presents an additional opportunity for research.

Evaluation of alternative weed management practices should continue taking a holistic approach. When considering the definition of sustainability, producing marketable fruit is critical for vineyard and wine-making production systems. Without salable and high-quality fruit, growers will be unable to sustain their livelihoods. Therefore, one of the next phases of research should consider the effects of alternative weed management practices on grape processing and wine-sensory characteristics.

APPENDIX

ADDITIONAL TABLES

CHAPTER 2 – Appendix Tables

CHAPTER 3 – Appendix Tables

Appendix Table 1a. Petiole nutrient content of 'Maréchal Foch' grapevines under four weed management treatments in 2008. Treatments were replicated four times in 16 plots. Observations were made on four grapevines per plot and averaged for each experimental unit. Approximately 150 to 200 petioles per plot were collected.

	(%)								(ppm)					
Treatment	N	NO_3-N	S	P	K	Mg	Ca	Na	B	Zn	Mn	Fe	Cu	Al
Cultivation	0.84 a[a]	0.004 a	0.12 a	0.23 a	1.74 a	0.47 a	1.46 a	0.01 a	32.2 a	73.5 a	23.0 a	26.0 a	10.3 a	4.8 a
Herbicide	0.84 a	0.003 a	0.12 a	0.23 a	1.75 a	0.47 a	1.40 a	0.01 a	32.0 a	76.0 a	21.5 a	26.0 a	11.8 a	4.8 a
Living mulch	0.86 a	0.004 a	0.11 a	0.22 a	1.46 a	0.48 a	1.43 a	0.01 a	32.5 a	72.8 a	24.8 a	28.0 a	10.8 a	3.0 a
Straw mulch	0.89 a	0.005 a	0.12 a	0.24 a	1.67 a	0.52 a	1.48 a	0.01 a	33.8 a	78.8 a	24.3 a	29.3 a	25.8 a	4.8 a

[a]Values are means of 16 experimental units with four replications; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 1b. Petiole nutrient content of ‘Maréchal Foch’ grapevines under four weed management treatments in 2009. Treatments were replicated four times in 16 plots. Observations were made on four grapevines per plot and averaged for each experimental unit. Approximately 150 to 200 petioles per plot were collected.

	(%)								(ppm)					
Treatment	N	NO_3-N	S	P	K	Mg	Ca	Na	B	Zn	Mn	Fe	Cu	Al
Cultivation	1.09 a[a]	0.01 a	0.13 a	0.23 a	1.56 a	0.56 a	1.55 a	0.01 a	37.0 a	91.8 a	28.8 a	31.0 a	8.3 a	1.0 a
Herbicide	1.22 a	0.02 a	0.13 a	0.26 a	1.77 a	0.6 a	1.57 a	0.01 a	37.5 a	89.5 a	29.0 a	28.5 a	9.5 a	1.0 a
Living mulch	1.22 a	0.01 a	0.12 a	0.23 a	1.49 a	0.56 a	1.5 a	0.01 a	36.0 a	84.3 a	28.5 a	29.3 a	8.0 a	1.5 a
Straw mulch	1.24 a	0.03 a	0.13 a	0.22 a	1.36 a	0.65 a	1.58 a	0.01 a	36.5 a	90.8 a	29.3 a	30.3 a	8.3 a	1.8 a

[a]Values are means of 16 experimental units with four replications; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 2a. Chemical indicators of soil quality from 'Maréchal Foch' vineyard soils (0 to 7.6 cm) receiving four weed management treatments in 2007. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Cultivation	6.29 a[a]	3.75 a	2.05 a	0.17 a	6.5 a	3.0 a	52.8 a	611 a	2067 a	370 a
Herbicide	6.18 a	3.55 a	1.94 a	0.18 a	5.0 a	3.3 a	47.8 a	253 a	1979 a	384 a
Living mulch	6.17 a	3.19 a	1.74 a	0.16 a	5.5 a	2.5 a	40.3 a	229 a	1989 a	377 a
Straw mulch	6.49 a	3.85 a	2.12 a	0.19 a	7.3 a	3.8 a	52.0 a	707 a	1948 a	388 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 2b. Chemical indicators of soil quality from 'Maréchal Foch' vineyard soils (0 to 7.6 cm) receiving four weed management treatments in 2008. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Cultivation	6.28 a[a]	3.1 a	1.7 a	0.16 a	1.3 a	3.8 a	29.3 a	202 a	1512 a	294 a
Herbicide	6.5 a	3.2 a	1.76 a	0.16 a	1.5 a	4.5 a	34.0 a	200 a	1467 a	276 a
Living mulch	6.35 a	2.8 a	1.52 a	0.16 a	2.0 a	4.5 a	30.8 a	193 a	1535 a	330 a
Straw mulch	6.64 ab	3.4 a	1.86 a	0.17 a	1.5 a	5.0 a	26.8 a	200 a	1595 a	299 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 2c. Chemical indicators of soil quality from 'Maréchal Foch' vineyard soils (0 to 7.6 cm) receiving four weed management treatments in 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Cultivation	6.43 a[a]	4.0 a	2.17 a	0.2 a	24.5 a	16.3 a	45.8 a	292 a	1704 a	359 a
Herbicide	6.41 a	4.0 a	2.18 a	0.2 a	23.0 a	13.3 a	43.3 a	313 a	1903 a	351 a
Living mulch	6.29 a	3.4 a	1.86 a	0.2 a	24.0 a	14.0 a	43.0 a	244 a	1731 a	356 a
Straw mulch	6.82 b	3.9 a	2.12 a	0.2 a	17.8 a	11.8 a	39.5 a	268 a	1697 a	334 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 3a. Chemical indicators of soil quality from 'Maréchal Foch' vineyard soils (7.6 to 15.2 cm) receiving four weed management treatments in 2007. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Cultivation	6.31 a[a]	2.98 a	1.62 a	0.16 a	3.0 a	3.3 a	19.3 a	236 a	2185 a	378 a
Herbicide	6.18 a	2.98 a	1.63 a	0.15 a	2.8 a	5.0 a	18.3 a	118 a	1985 a	411 a
Living mulch	6.17 a	2.65 a	1.44 a	0.14 a	2.5 a	4.3 a	12.8 a	101 a	2015 a	376 a
Straw mulch	6.49 ab	2.98 a	1.63 a	0.16 a	5.0 a	4.5 a	27.0 b	238 a	1854 a	368 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 3b. Chemical indicators of soil quality from 'Maréchal Foch' vineyard soils (7.6 to 15.2 cm) receiving four weed management treatments in 2008. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Cultivation	6.23 a[a]	2.43 a	1.34 a	0.13 a	1.0 a	4.8 a	12.3 a	144 a	1563 a	362 a
Herbicide	6.48 a	2.85 a	1.55 a	0.14 a	1.8 a	5.0 a	11.0 a	147 a	1601 a	331 a
Living mulch	6.3 a	2.18 a	1.19 a	0.12 a	1.8 a	4.3 a	16.0 a	124 a	1540 a	335 a
Straw mulch	6.41 a	2.83 a	1.55 a	0.14 a	1.3 a	4.5 a	11.0 a	142 a	1794 a	335 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 3c. Chemical indicators of soil quality from 'Maréchal Foch' vineyard soils (7.6 to 15.2 cm) receiving four weed management treatments in 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Cultivation	6.17 a[a]	2.88 a	1.58 a	0.15 a	16.5 a	7.3 a	20.0 a	186 a	1846 a	388 a
Herbicide	6.47 a	3.18 a	1.73 a	0.16 a	23.8 a	16.8 a	22.0 a	202 a	1979 a	378 a
Living mulch	6.4 a	2.53 a	1.38 a	0.14 a	23.3 a	16.3 a	22.5 a	167 a	1736 a	362 a
Straw mulch	6.53 a	2.95 a	1.63 a	0.15 a	22.8 a	10.3 a	19.0 a	180 a	1839 a	359 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 4. Percentage stable aggregate content from 'Maréchal Foch' vineyard soils receiving four weed management treatments, 2007 to 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

	(0 to 7.6 cm)			(7.6 to 15.2 cm)		
Treatment	2007	2008	2009	2007	2008	2009
Cultivation	11 a[a]	31 a	42 a	23 a	12 a	16 a
Herbicide	8 a	31 a	44 a	15 a	17 a	17 a
Living mulch	11 a	28 a	33 a	17 a	12 a	13 a
Straw mulch	10 a	34 a	42 a	24 a	18 a	22 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 5. Biological indicators of soil quality from ‘Maréchal Foch’ vineyard soils (0 to 7.6 cm) receiving four weed management treatments, 2007 to 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit. Biological activity was measured by potential soil enzymatic activity and was quantified via fluorescein diacetate (FDA) hydrolysis.

	Fluorescein released (mg kg^{-1} soil 3 h^{-1})			
Treatment	2007	2008	2009	2007 to 2009
Cultivation	211 a[a]	210 a	255 a	225 a
Herbicide	205 a	216 a	275 a	232 a
Living mulch	232 a	228 a	266 a	242 a
Straw mulch	220 a	227 a	265 a	237 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at *P* $\leq$ 0.05 using a Tukey-Kramer adjustment.

Appendix Table 6. Biological indicators of soil quality from ‘Maréchal Foch’ vineyard soils (7.6 to 15.2 cm) receiving four weed management treatments, 2007 to 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit. Biological activity was measured by potential soil enzymatic activity and was quantified via fluorescein diacetate (FDA) hydrolysis.

	Fluorescein released (mg kg^{-1} soil 3 h^{-1})			
Treatment	2007	2008	2009	2007 to 2009
Cultivation	107 a[a]	164 a	145 a	139 a
Herbicide	124 a	148 a	163 a	145 a
Living mulch	105 a	133 a	130 a	123 a
Straw mulch	128 a	163 a	163 a	151 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Table 7. Populations of horizontal-dwelling earthworms collected by hand-sorting 25 cm^3 of vineyard surface soil, spring 2010.

Treatment	Earthworm count (no.)
Cultivation	4 a[a]
Herbicide	2 a
Living mulch	2 a
Straw mulch	23 b

[a]Means from 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 8a. Petiole nutrient content of ‘Reliance’ grapevines under four weed management and irrigation treatments in 2008. Treatments were replicated four times in 16 plots. Observations were made on four grapevines per plot and averaged for each experimental unit. Approximately 150 to 200 petioles per plot were collected.

	(%)								(ppm)					
Treatment	N	NO_3-N	S	P	K	Mg	Ca	Na	B	Zn	Mn	Fe	Cu	Al
Herbicide	0.80 a[a]	0.002 a	0.08 a	0.2 a	1.96 a	0.32 a	0.83 a	0.01 a	27.0 a	42.0 a	21.5 a	39.0 a	15.5 a	1.0 a
Herbicide + irrigation	0.77 a	0.002 a	0.07 a	0.19 a	1.59 a	0.33 a	0.86 a	0.01 a	26.0 a	44.0 a	20.0 a	64.5 a	17.8 a	1.0 a
Living mulch	0.81 a	0.003 a	0.08 a	0.19 a	1.58 a	0.34 a	0.88 a	0.01 a	27.0 a	48.0 a	22.0 a	43.7 a	23.3 a	1.0 a
Living mulch + irrigation	1.25 a	0.002 a	0.08 a	0.20 a	1.7 a	0.32 a	0.95 a	0.01 a	27.3 a	40.5 a	33.6 a	30.8 a	9.8 a	1.0 a

[a]Values are means of 16 experimental units with four replications; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 8b. Petiole nutrient content of ‘Reliance’ grapevines under four weed management and irrigation treatments in 2009. Treatments were replicated four times in 16 plots. Observations were made on four grapevines per plot and averaged for each experimental unit. Approximately 150 to 200 petioles per plot were collected.

	(%)								(ppm)					
Treatment	N	NO_3-N	S	P	K	Mg	Ca	Na	B	Zn	Mn	Fe	Cu	Al
Herbicide	0.97 a[a]	0.01 a	0.06 a	0.26 a	2.05 a	0.28 a	0.98 a	0.01 a	31.8 a	40.8 a	30.0 a	21.3 a	8.0 a	2.0 a
Herbicide + irrigation	0.87 a	0.01 a	0.08 a	0.25 a	1.95 a	0.29 a	1.1 a	0.01 a	31.5 a	43.5 a	29.8 a	24.5 a	7.3 a	1.8 a
Living mulch	0.93 a	0.01 a	0.07 a	0.23 a	1.86 a	0.28 a	1.0 a	0.01 a	32.8 a	42.7 a	32.5 a	22.6 a	8.3 a	2.0 a
Living mulch + irrigation	1.02 a	0.02 a	0.08 a	0.27 a	2.4 a	0.24 a	0.95 a	0.01 a	33.5 a	42.2 a	34.5 a	22.6 a	12 a	1.1 a

[a]Values are means of 16 experimental units with four replications; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 9a. Petiole nutrient content of ‘Swenson Red’ grapevines under four weed management and irrigation treatments in 2008. Treatments were replicated four times in 16 plots. Observations were made on four grapevines per plot and averaged for each experimental unit. Approximately 150 to 200 petioles per plot were collected.

	(%)								(ppm)					
Treatment	N	NO_3-N	S	P	K	Mg	Ca	Na	B	Zn	Mn	Fe	Cu	Al
Herbicide	0.77 a[a]	0.004 a	0.06 a	0.21 a	1.0 a	0.48 a	1.16 a	0.01 a	37.5 a	51.0 a	22.75 a	22.0 a	9.0 a	1.0 a
Herbicide + irrigation	0.7 a	0.002 b	0.06 a	0.19 a	0.82 a	0.46 a	1.02 ab	0.01 a	32.3 b	47.3 a	23.0 a	26.8 a	12.2 a	1.8 a
Living mulch	0.72 a	0.002 b	0.06 a	0.19 a	0.96 a	0.44 a	0.97 b	0.01 a	36.9 ab	45.0 a	20.0 a	23.9 a	8.3 a	1.0 a
Living mulch + irrigation	0.71 a	0.002 b	0.06 a	0.23 a	1.2 a	0.51 a	1.06 ab	0.01 a	38.0 a	53.0 a	18.5 a	27.8 a	18.5 a	1.3 a

[a]Values are means of 16 experimental units with four replications; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 9b. Petiole nutrient content of 'Swenson Red' grapevines under four weed management and irrigation treatments in 2009. Treatments were replicated four times in 16 plots. Observations were made on four grapevines per plot and averaged for each experimental unit. Approximately 150 to 200 petioles per plot were collected.

	(%)								(ppm)					
Treatment	N	NO_3-N	S	P	K	Mg	Ca	Na	B	Zn	Mn	Fe	Cu	Al
Herbicide	0.92 a[a]	0.01 a	0.07 a	0.17 a	0.7 a	0.57 a	1.5 a	0.01 a	38.3 a	61.8 a	34.5 a	33.0 a	4.8 a	3.8 a
Herbicide + irrigation	0.83 a	0.02 a	0.06 a	0.16 a	0.62 a	0.62 a	1.5 a	0.01 a	36.8 a	57.8 a	41.5 a	28.2 a	4.0 a	0.6 a
Living mulch	0.84 a	0.01 a	0.07 a	0.2 a	0.95 a	0.49 a	1.3 a	0.01 a	38.7 a	49.1 a	35.0 a	33.0 a	4.1 a	3.0 a
Living mulch + irrigation	0.81 a	0.01 a	0.07 a	0.2 a	0.89 a	0.53 a	1.3 a	0.01 a	37.8 a	50.8 a	31.3 a	32.0 a	4.8 a	4.5 a

[a]Values are means of 16 experimental units with four replications; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 10a. Chemical indicators of soil quality from 'Reliance' vineyard soils (0 to 7.6 cm) receiving four weed management and irrigation treatments in 2007. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Herbicide	6.28 a[a]	3.23 a	1.76 a	0.17 a	4.0 a	3.8 a	35.3 a	196 a	1965 a	354 a
Herbicide + irrigation	5.58 a	2.78 a	1.51 a	0.16 a	4.5 a	4.0 a	26.8 a	166 a	1881 a	356 a
Living mulch	5.85 a	3.08 a	1.69 a	0.16 a	6.5 a	5.0 a	46.8 a	220 a	1990 a	376 a
Living mulch + irrigation	5.84 a	3.08 a	1.68 a	0.17 a	4.5 a	4.8 a	41.5 a	209 a	1760 a	340 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 10b. Chemical indicators of soil quality from 'Reliance' vineyard soils (0 to 7.6 cm) receiving four weed management and irrigation treatments in 2008. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Herbicide	6.4 a[a]	3.40 a	1.85 a	0.17 a	2.25 a	7.0 a	43.8 a	243 a	1567 a	314 a
Herbicide + irrigation	5.81 a	3.0 a	1.63 a	0.16 a	1.75 a	5.8 a	35.3 a	213 a	1494 a	305 a
Living mulch	6.13 a	3.45 a	1.9 a	0.18 a	2.25 a	5.0 a	45.3 a	242 a	1535 a	318 a
Living mulch + irrigation	6.03 a	3.35 a	1.83 a	0.17 a	2.5 a	8.3 a	45.0 a	262 a	1530 a	311 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 10c. Chemical indicators of soil quality from ‘Reliance’ vineyard soils (0 to 7.6 cm) receiving four weed management and irrigation treatments in 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Herbicide	6.48 a[a]	3.35 a	1.84 a	0.18 a	12.5 a	27.8 a	22.8 a	166 a	1578 a	291 a
Herbicide + irrigation	5.82 a	2.85 a	1.57 a	0.16 a	15.75 a	32.0 a	20.3 a	164 a	1532 a	311 a
Living mulch	6.12 a	3.15 a	1.73 a	0.17 a	7.5 a	31.25 a	26.3 a	200 a	1522 a	325 a
Living mulch + irrigation	5.99 a	3.45 a	1.89 a	0.18 a	14.75 a	28.0 a	31.3 a	183 a	1444 a	297 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 11a. Chemical indicators of soil quality from ‘Reliance’ vineyard soils (7.6 to 15.2 cm) receiving four weed management and irrigation treatments in 2007. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Herbicide	6.38 a[a]	2.70 a	1.48 a	0.13 a	3.5 a	3.5 a	9.5 a	118 a	2107 a	363 a
Herbicide + irrigation	5.88 a	2.20 a	1.20 a	0.11 a	2.25 a	3.75 a	7.5 a	527 a	1851 a	359 a
Living mulch	6.09 a	2.53 a	1.38 a	0.12 a	2.5 a	3.5 a	10.3 a	121 a	1888 a	370 a
Living mulch + irrigation	6.0 a	2.58 a	1.40 a	0.13 a	2.75 a	4.0 a	14.0 a	125 a	1869 a	362 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 11b. Chemical indicators of soil quality from 'Reliance' vineyard soils (7.6 to 15.2 cm) receiving four weed management and irrigation treatments in 2008. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Herbicide	6.43 a[a]	2.75 a	1.50 a	0.14 a	1.25 a	4.25 a	20.3 a	163 a	1577 a	321 a
Herbicide + irrigation	5.89 ab	2.43 a	1.33 a	0.13 a	1.25 a	4.5 a	18.0 a	164 a	1607 a	346 a
Living mulch	6.23 a	2.93 a	1.58 a	0.15 a	1.50 a	4.75 a	21.3 a	168 a	1531 a	330 a
Living mulch + irrigation	6.08 a	2.75 a	1.51 a	0.14 a	1.25 a	4.5 a	21.8 a	176 a	1521 a	322 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 11c. Chemical indicators of soil quality from 'Reliance' vineyard soils (7.6 to 15.2 cm) receiving four weed management and irrigation treatments in 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Herbicide	6.45 a[a]	2.78 a	1.51 a	0.15 a	13.75 a	23.0 a	9.0 a	114 a	1822 a	345 a
Herbicide + irrigation	6.03 a	2.3 a	1.26 a	0.13 a	17.5 a	30.8 a	8.5 a	108 a	1707 a	362 a
Living mulch	6.23 a	2.55 a	1.38 a	0.14 a	13.0 a	25.0 a	10.5 a	125 a	1558 a	356 a
Living mulch + irrigation	6.1 a	2.65 a	1.44 a	0.14 a	8.5 a	26.0 a	12.75 a	118 a	1526 a	324 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 12a. Chemical indicators of soil quality from 'Swenson Red' vineyard soils (0 to 7.6 cm) receiving four weed management and irrigation treatments in 2007. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Herbicide	5.73 a[a]	3.3 a	1.8 a	0.17 a	7.3 a	4.0 a	46.3 a	245 a	1986 a	370 a
Herbicide + irrigation	5.96 a	2.9 a	1.57 a	0.15 a	5.5 a	4.3 a	44.0 a	223 a	1902 a	387 a
Living mulch	5.02 a	3.5 a	1.93 a	0.18 a	6.3 a	4.8 a	48.8 a	257 a	1927 a	380 a
Living mulch + irrigation	5.61 a	3.3 a	1.81 a	0.17 a	5.5 a	4.5 a	49.5 a	247 a	1925 a	360 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 12b. Chemical indicators of soil quality from 'Swenson Red' vineyard soils (0 to 7.6 cm) receiving four weed management and irrigation treatments in 2008. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Herbicide	6.16 a[a]	3.73 a	2.04 a	0.19 a	2.75 a	4.0 a	41.0 a	252 a	1648 a	307 a
Herbicide + irrigation	6.33 a	3.23 a	1.77 a	0.17 a	4.25 a	3.8 a	39.8 a	272 a	1519 a	329 a
Living mulch	5.93 a	3.83 a	2.09 a	0.19 a	4.5 a	4.0 a	39.5 a	233 a	1760 a	342 a
Living mulch + irrigation	5.91 a	3.52 a	1.93 a	0.17 a	4.0 a	4.3 a	54.0 a	325 a	1612 a	337 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 12c. Chemical indicators of soil quality from 'Swenson Red' vineyard soils (0 to 7.6 cm) receiving four weed management and irrigation treatments in 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Herbicide	6.13 a[a]	3.15 a	1.72 a	0.15 a	13.25 a	31.3 a	45.5 a	230 a	1529 a	290 a
Herbicide + irrigation	6.29 a	2.78 a	1.52 a	0.14 ab	11.5 ab	34.0 a	42.5 a	201 a	1487 a	319 a
Living mulch	5.83 a	3.8 a	2.09 a	0.19 a	29.0 a	40.3 a	37.8 a	224 a	1483 a	306 a
Living mulch + irrigation	5.9 a	3.4 a	1.87 a	0.16 a	22.75 a	44.3 a	44.0 a	239 a	1530 a	321 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 13a. Chemical indicators of soil quality from 'Swenson Red' vineyard soils (7.6 to 15.2 cm) receiving four weed management and irrigation treatments in 2007. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Herbicide	5.98 a[a]	2.43 a	1.33 a	0.13 a	3.75 a	3.8 a	17.3 a	158 a	1946 a	361 a
Herbicide + irrigation	5.97 a	2.2 a	1.21 a	0.12 a	3.25 a	3.8 a	16.3 a	137 a	1855 a	380 a
Living mulch	5.75 a	2.93 a	1.59 a	0.15 a	3.25 a	4.0 a	18.3 a	151 a	2040 a	384 a
Living mulch + irrigation	5.77 a	2.65 a	1.44 a	0.14 a	2.75 a	3.3 a	19.8 a	602 a	1955 a	363 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 13b. Chemical indicators of soil quality from ‘Swenson Red’ vineyard soils (7.6 to 15.2 cm) receiving four weed management and irrigation treatments in 2008. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Herbicide	6.18 a[a]	2.95 a	1.60 a	0.14 a	2.5 a	3.8 a	17.0 a	169 a	1656 a	331 a
Herbicide + irrigation	6.26 a	2.58 a	1.41 a	0.13 a	3.25 a	5.0 a	17.8 a	181 a	1488 a	328 a
Living mulch	5.94 a	3.15 a	1.74 a	0.15 a	2.5 a	3.8 a	15.0 a	129 a	1731 a	324 a
Living mulch + irrigation	5.92 a	2.93 a	1.60 a	0.14 a	2.75 a	4.0 a	26.5 a	253 a	1568 a	344 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 13c. Chemical indicators of soil quality from 'Swenson Red' vineyard soils (7.6 to 15.2 cm) receiving four weed management and irrigation treatments in 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

		(%)			(ppm)					
Treatment	pH	Organic matter	Total organic carbon	Total organic nitrogen	NO_3-N	NH_4-N	Bray-P	K	Ca	Mg
Herbicide	6.12 a[a]	2.4 a	1.31 a	0.12 a	17.5 a	35.3 a	19.5 a	144 a	1519 a	332 a
Herbicide + irrigation	6.23 a	2.4 a	1.28 a	0.12 a	15.3 a	35.0 a	16.8 a	134 a	1602 a	363 a
Living mulch	5.64 b	3.1 a	1.69 a	0.15 a	12.5 a	29.0 a	25.0 a	165 a	1589 a	320 a
Living mulch + irrigation	6.36 a	2.5 a	1.37 a	0.13 a	4.5 a	37.8 a	20.3 a	123 a	1653 a	325 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 14. Biological indicators of soil quality from 'Reliance' vineyard soils (0 to 7.6 cm) receiving four weed management and irrigation treatments, 2007 to 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit. Biological activity was measured by potential soil enzymatic activity and was quantified via fluorescein diacetate (FDA) hydrolysis.

	Fluorescein released (mg kg^{-1} soil 3 h^{-1})		
Treatment	2007	2008	2009
Herbicide	167 a[a]	197 a	224 a
Herbicide + irrigation	156 a	167 a	253 a
Living mulch	173 a	174 a	233 a
Living mulch + irrigation	188 a	152 a	278 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 15. Biological indicators of soil quality from 'Reliance' vineyard soils (7.6 to 15.2 cm) receiving four weed management and irrigation treatments, 2007 to 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit. Biological activity was measured by potential soil enzymatic activity and was quantified via fluorescein diacetate (FDA) hydrolysis.

	Fluorescein released (mg kg^{-1} soil 3 h^{-1})		
Treatment	2007	2008	2009
Herbicide	146 a[a]	128 a	92 a
Herbicide + irrigation	68 ab	85 a	85 a
Living mulch	91 a	119 a	98 a
Living mulch + irrigation	106 a	110 a	115 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 16. Biological indicators of soil quality from 'Swenson Red' vineyard soils (0 to 7.6 cm) receiving four weed management and irrigation treatments, 2007 to 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit. Biological activity was measured by potential soil enzymatic activity and was quantified via fluorescein diacetate (FDA) hydrolysis.

	Fluorescein released (mg kg^{-1} soil 3 h^{-1})		
Treatment	2007	2008	2009
Herbicide	162 a[a]	243 a	233 a
Herbicide + irrigation	169 a	184 a	232 a
Living mulch	175 a	208 a	295 a
Living mulch + irrigation	164 a	245 a	299 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 17. Biological indicators of soil quality from ‘Swenson Red’ vineyard soils (7.6 to 15.2 cm) receiving four weed management and irrigation treatments, 2007 to 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit. Biological activity was measured by potential soil enzymatic activity and was quantified via fluorescein diacetate (FDA) hydrolysis.

	Fluorescein released (mg kg^{-1} soil 3 h^{-1})		
Treatment	2007	2008	2009
Herbicide	147 a[a]	147 a	149 a
Herbicide + irrigation	137 a	162 a	154 a
Living mulch	192 a	156 a	191 a
Living mulch + irrigation	147 a	146 a	155 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 18. Matric water potential (kPa) collected from 15.2 cm tensiometers in rows of 'Reliance' receiving one of four weed management and irrigation treatments, 2008 and 2009.

	2008		2009		
Treatment	July[a]	Aug	June	July	Aug
Herbicide	5.1 a[b]	13.4 a	3.5 a	6.7 a	11.2 a
Herbicide + irrigation	3.3 a	7.0 a	5.5 a	7.5 a	8.0 a
Living mulch	7.5 a	15.0 a	0.2 a	7.4 a	0.3 a
Living mulch + irrigation	3.5 a	10.5 a	6.5 a	16.1 a	12.6 a

[a]No June 2008 data collected due to flooding.
[b]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 19. Matric water potential (kPa) collected from 30.5 cm tensiometers in rows of ‘Reliance’ receiving one of four weed management and irrigation treatments, 2008 and 2009.

	2008		2009		
Treatment	July[a]	Aug	June	July	Aug
Herbicide	4.9 a[b]	12.8 a	2.0 a	3.8 a	13.8 a
Herbicide + irrigation	4.3 ab	7.6 a	2.0 a	2.2 a	2.2 a
Living mulch	10.9 b	12.3 a	2.7 a	12.2 a	29.5 a
Living mulch + irrigation	7.2 ab	10.1 a	4.0 a	7.8 a	9.3 a

[a]No June 2008 data collected due to flooding.
[b]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 20. Matric water potential (kPa) collected from 15.2 cm tensiometers in rows of ‘Swenson Red’ receiving one of four weed management and irrigation treatments, 2008 and 2009.

	2008		2009		
Treatment	July[a]	Aug	June	July	Aug
Herbicide	7.6 a[b]	9.3 a	1.2 a	2.3 a	4.2 a
Herbicide + irrigation	8.0 a	16.5 a	3.5 a	5.5 a	5.9 a
Living mulch	11.2 a	17.5 a	7.1 a	18.6 a	4.1 a
Living mulch + irrigation	10.3 a	17.9 a	8.0 a	19.0 a	21.9 b

[a]No June 2008 data collected due to flooding.
[b]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 21. Matric water potential (kPa) collected from 30.5 cm tensiometers in rows of ‘Swenson Red’ receiving one of four weed management and irrigation treatments, 2008 and 2009.

	2008		2009		
Treatment	July[a]	Aug	June	July	Aug
Herbicide	4.9 a[b]	5.0 a	4.0 a	4.5 a	4.6 a
Herbicide + irrigation	6.3 a	7.1 a	2.7 a	2.5 a	2.5 a
Living mulch	14.1 a	12.1 a	7.4 a	13.6 a	20.6 a
Living mulch + irrigation	6.8 a	8.9 a	5.8 a	10.3 a	25.2 a

[a]No June 2008 data collected due to flooding.
[b]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 22. Percentage stable aggregate content from 'Reliance' vineyard soils receiving four weed management and irrigation treatments, 2007 to 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

	(0 to 7.6 cm)			(7.6 to 15.2 cm)		
Treatment	2007	2008	2009	2007	2008	2009
Herbicide	13 a[a]	22 a	26 a	13 a	7 a	10 a
Herbicide + irrigation	15 a	21 a	31 a	12 a	8 a	12 a
Living mulch	12 a	19 a	28 a	8 a	9 a	12 a
Living mulch + irrigation	14 a	19 a	24 a	10 a	8 a	8 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

Appendix Table 23. Percentage stable aggregate content from 'Swenson Red' vineyard soils receiving four weed management and irrigation treatments, 2007 to 2009. Treatments were replicated four times in 16 plots. Measurements of indicators were collected from three samples per plot and averaged for each experimental unit.

	(0 to 7.6 cm)			(7.6 to 15.2 cm)		
Treatment	2007	2008	2009	2007	2008	2009
Herbicide	18 a[a]	15 a	14 a	8.9 a	17 a	12 a
Herbicide + irrigation	18 a	17 a	17 a	9.0 a	13 a	12 a
Living mulch	16 a	25 a	32 b	10 a	16 a	17 a
Living mulch + irrigation	18 a	22 a	28 ab	8 a	13 a	13 a

[a]Means from four replications of 16 experimental units; means with the same letter within a column are not different at $P \leq 0.05$ using a Tukey-Kramer adjustment.

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